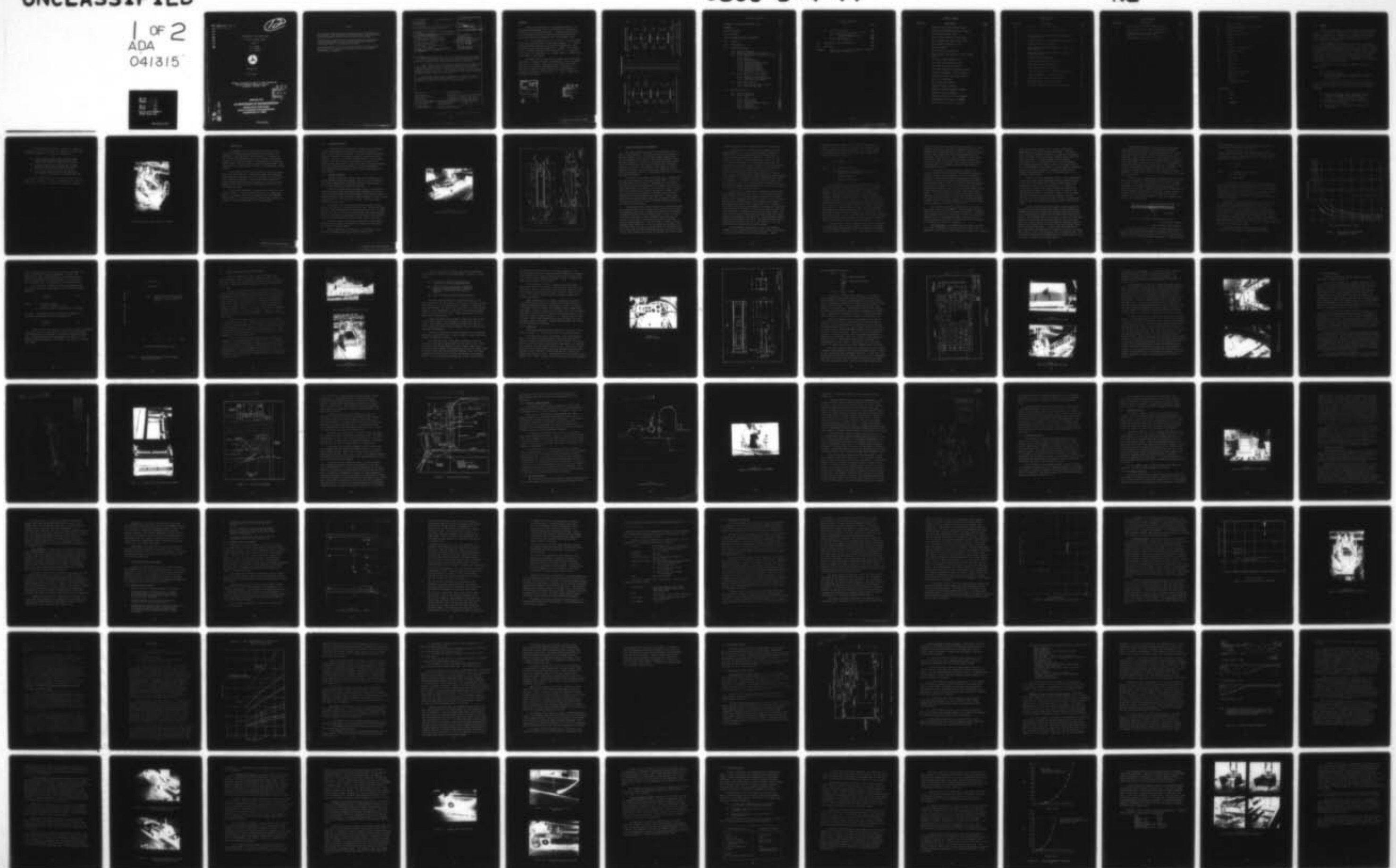
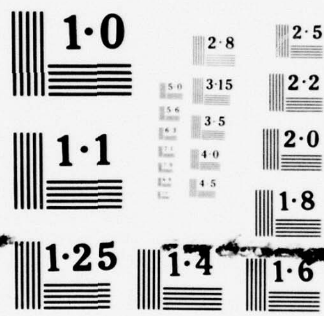
AD-A041 315 SEAWARD INTERNATIONAL INC FALLS CHURCH VA F/G 13/2
DEVELOPMENT OF A STREAMING-FIBER OIL SPILL CONTROL SYSTEM, STAG--ETC(U)
DEC 76 R L BEACH, D W DURFEE, R J POWERS DOT-CG-40217-A
UNCLASSIFIED USCG-D-4-77 NL

1 OF 2
ADA
041315





NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

REPORT NO. - CG-D-4-77
Task No. 4111.8.2

DEVELOPMENT OF A STREAMING-FIBER OIL SPILL CONTROL SYSTEM STAGE II

R. L. BEACH
D. W. DURFEE
R. J. POWERS

DECEMBER 1976

FINAL REPORT

Document is available to the U. S. public through the National Technical Information Service, Springfield, Virginia 22161

PREPARED FOR

U.S. DEPARTMENT OF TRANSPORTATION

UNITED STATES COAST GUARD
OFFICE OF RESEARCH AND DEVELOPMENT
WASHINGTON, D.C. 20590

NOTICE

Technical Report Documentation Page

1. Report No. USCG-D-4-77	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Development of a Streaming-Fiber Oil Spill Control System, Stage II.		5. Report Date December, 1976 6. Performing Organization Code 8. Performing Organization Report No.
7. Author(s) R.L. Beach, D.W. Durfee, R.J. Powers		
9. Performing Organization Name and Address Seaward International, Inc. 6269 Leesburg Pike, Suite 204 Falls Church, Virginia 22044		10. Work Unit No. (TRAIS) 4111.8.2 11. Contract or Grant No. DOT-CG-40,217-A 13. Type of Report and Period Covered Final Report 26 Sep 75-22 Nov 76
12. Sponsoring Agency Name and Address Department of Transportation U. S. Coast Guard Office of Research and Development Washington, D. C. 20590		14. Sponsoring Agency Code G-DET-1/TRPT
15. Supplementary Notes		

16. Abstract

Seaward International, Inc. has developed the streaming fiber oil spill control concept into a large-scale model, and tested it successfully under simulated field conditions.

The program involved design and construction of the large-scale model, and testing at the EPA's OHMSETT test facility. Tests were conducted in a variety of conditions at speeds ranging from 2 to 6 knots. Test results showed that the concept works, although there are some performance limitations with the present design, principally in waves.

Design of a full-scale prototype is presented, which includes features having the potential to overcome the present limitations and meet or exceed all design goals.

17. Key Words	18. Distribution Statement
Oil Skimmers Oil Spill Control Pollution Fast Current Oil Spill Control	Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22151

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	151	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

410055

FOREWORD

This report presents the second-stage results of an engineering development study of a method for controlling spilled oil on high-current waters. Seaward International, Inc., performed this work under Contract DOT-CG-40217-A, during the period 26 September 1975 to 22 November 1976.

LT J. H. Getman and LT R. Ard of the U. S. Coast Guard served as Project Officers during this program. R. L. Beach served as Project Manager from Seaward International, Inc. Development work was performed by R. L. Beach, D. W. Durfee, and R. J. Powers, who were ably assisted by J. D. Brown and P. F. Brown. M. Krenitsky, L. S. Brown, and F. A. March also contributed in the effort.

The model towing tests were performed at the Davidson Laboratory, Stevens Institute of Technology, under the direction of Dr. E. Numata. The large-scale model tests were performed at the EPA's OHMSETT facility in Leonardo, N. J. The Spiltrol Harbor Skimmer modified for this program is marketed by Seaward International, Inc., under license from the Shell Oil Company.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

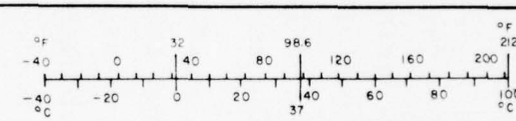


TABLE OF CONTENTS

TABLE OF CONTENTS
(cont.)

LIST OF FIGURES

LIST OF FIGURES
(cont.)

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

d	Droplet diameter
d_e	Equivalent diameter of fiber array
f	Friction factor
g	Gravitational constant
h	Height
L	Length
P	Power
Q	Volumetric oil flow rate
Re	Reynolds number
U	Velocity
w	Belt width
We	Weber number
δ	Spacing
Δ	Incremental
η	Propulsive efficiency
μ	Absolute viscosity
ρ	Density
σ	Interfacial Tension

Subscripts:

b	Belt
w	Water
o	Oil
c	Critical

1.0 SUMMARY

Seaward International, Inc., has developed the streaming-fiber oil spill control concept into a large-scale model and tested it successfully at speeds up to 6 knots under simulated field conditions. The work was performed under U. S. Coast Guard contract DOT-CG-40217-A.

The streaming-fiber concept utilizes long, continuous fibers oriented parallel to the water flow. The fibers function by slowing down and thickening the incoming oil, so that recovery by conventional means can be performed. Problem areas identified previously (Stage I) were solved during the initial stages of this program, and the results were incorporated into a large-scale model for full-scale testing at the OHMSETT test facility. This model is shown in the figure.

The results of system tests at OHMSETT indicated in general that:

- the concept works.
- there are limitations to the system as presently designed, particularly in waves and in viscous oil performance.

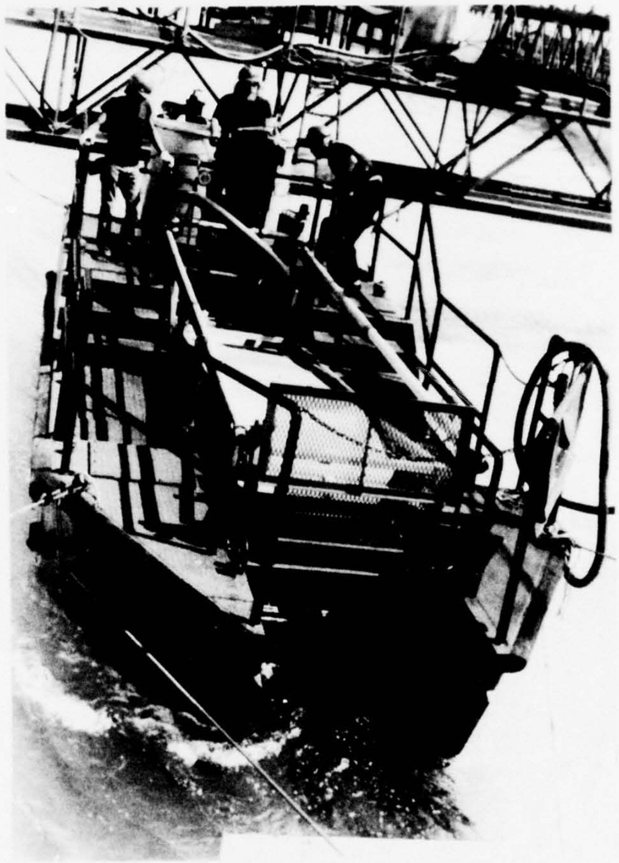
The test skimmer was constructed around the hull of a Spiltrol Harbor Skimmer which was modified with a special bow shape for fast-current use. Special features of the skimmer included:

- a rigid fiber support box, which was mounted between the skimmer hulls, and which could be elevated to change the depth of fibers.
- an endless belt above the fibers, which was designed to sweep viscous oil to the rear of the device for recovery.
- a weir and sump, from which the recovered oil was pumped.

A proposed prototype skimmer, modified to remove the limitations of the test skimmer, is described. Significant differences between it and the test skimmer are:

- a free-floating fiber array with adjustable fiber tension replaces the fiber box, permitting the fibers to conform to the waves.
- a porous, oleophilic rotating belt, located below the fiber array to catch any escaping oil, replaces the belt above the fibers.
- a roller to squeeze the oil from the belt, and floating suction heads to recover the oil, replace the function of the weir and sump.

Further development work on these modifications is recommended, followed by actual incorporation into the large-scale model and additional performance testing at OHMSETT.



LARGE-SCALE MODEL DURING TESTS AT OHMSETT

2.0 INTRODUCTION

In response to the Coast Guard's need for a fast-current oil skimming system, Seaward International, Inc., undertook the present development program. In Stage I of the program the feasibility of using an array of streaming fibers to slow down and recover a fast-moving oil slick was demonstrated. Several areas for additional development were identified, and initial work in Stage II concentrated on these areas.

As a result of the studies conducted initially during Stage II, the design for a large-scale model was developed. By implementing this design in the modified hull of an available, commercial skimmer, a large-scale model capable of actual cleanup operations was constructed. Testing of this model was performed at the EPA's OHMSETT test facility in Leonardo, New Jersey.

This report describes the programs and results of the Stage II effort. A thorough description of the large-scale model is included, as well as a description of the OHMSETT test program. A prototype design, incorporating several new features to improve performance, is also described.

3.0 LARGE-SCALE MODEL

A description of the design, hardware, and functioning of the large-scale model developed during this program is given in the following sections. This model was the principal test item from which conclusions could be drawn during the program. Because of its size, seaworthiness, and operational features, the model itself could actually be used for oil spill cleanup operations in the field, under limited conditions. A review of the theory of operation is also presented, as well as additional insights gained during other phases of the testing.

3.1 Overall Features

Figure 1 shows an overall view of the actual model, as constructed during the program. Figure 2 is a drawing of the model cross-section, which may show more clearly some of the overall features to be discussed below.

The hull is constructed of steel, and is of a modified catamaran design with the forward hulls separated to enclose the oil skimming mechanism on two sides. The overall envelope dimensions are 32 feet in length (outdrive down), 10 feet 2 inches in height, and 10 feet 8 inches in width (including bumper strips along the sides).

The fibers are strung around vertical supports, which are in turn fixed to a three-sided rigid box. Behind the fiber array is a weir and sump for collecting the oil. Oil is pumped out of the sump by a positive displacement pump located inside the hull. The box can be lowered or elevated by four hydraulically driven jack screws located at each corner of the box.

Over the fibers is a hydraulically driven endless belt which is used in some circumstances to sweep oil from above the fibers to the weir area.

Debris protection is provided by a trash gate at the bow and a removable net fixed over the fiber array.

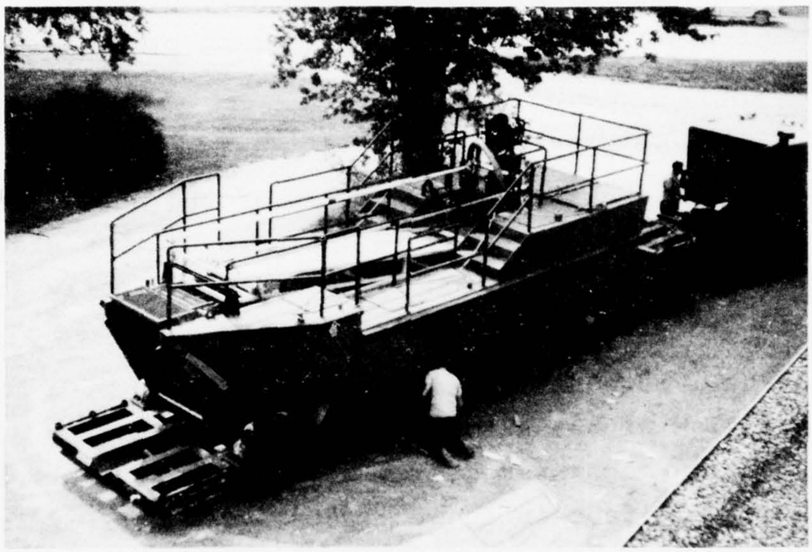


FIGURE 1
OVERALL VIEW OF LARGE-SCALE MODEL

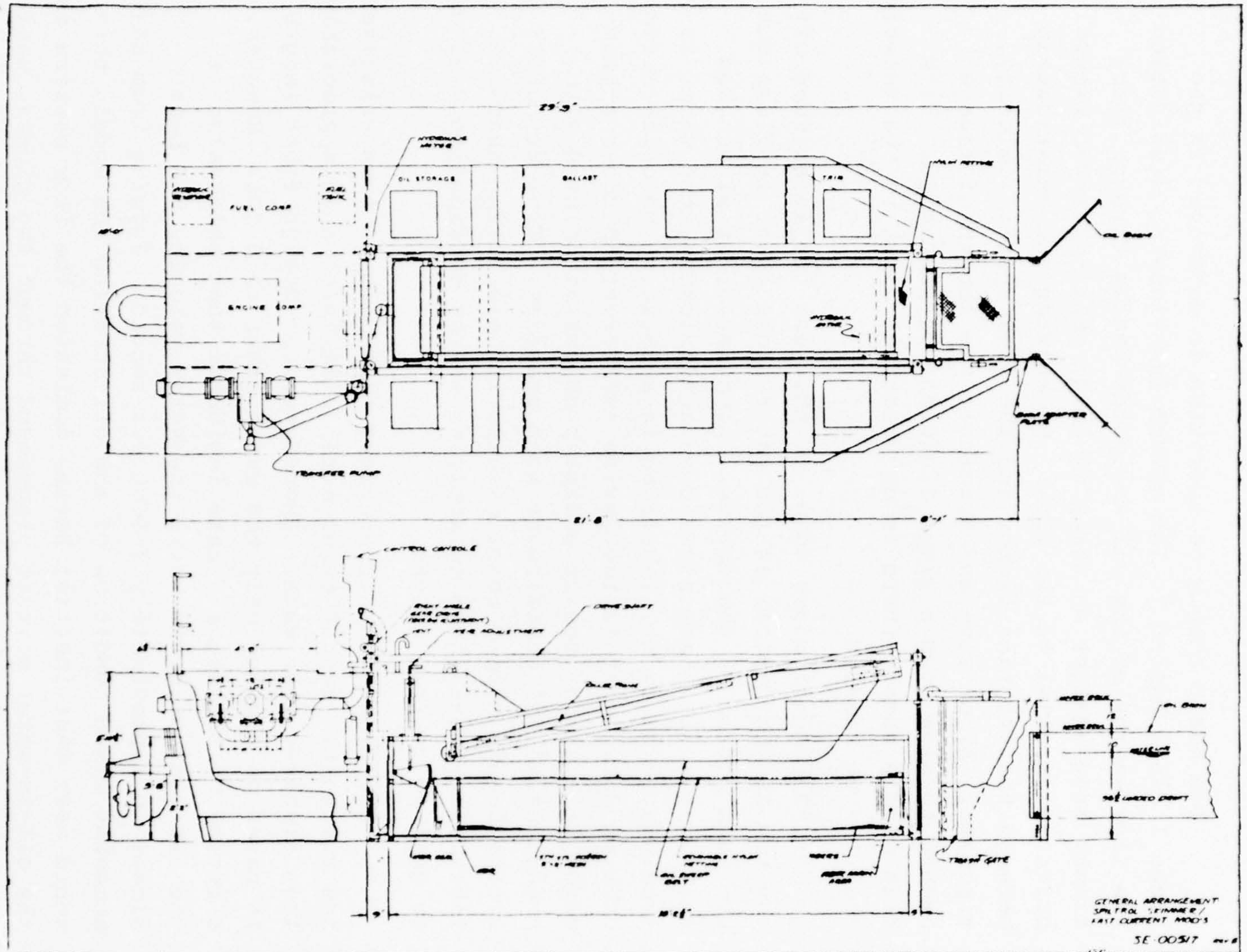


FIGURE 2
GENERAL ARRANGEMENT - LARGE SCALE MODEL

3.2 Review of Theoretical Operation

The basic theory of operation is described in the Stage I Final Report [1]. The system functions by dissipating the flow energy of the oil and water phases through frictional drag against an array of long, small-diameter fibers, oriented parallel to the flow. By knowing the relationship between the friction factor and the flow system (velocity, viscosity, fiber size and spacing), the length of fibers needed to slow down a given fluid can be predicted. With this simple theory there is no practical limit to the velocity that can be handled.

As the oil slows down, it thickens and is skimmed off the top of the device; as the water slows down, it flows out the open bottom of the device. Lindenmuth, et al [2] showed that as the oil phase slows down and thickens, the water is accelerated below it, resulting in a relative velocity difference at some point in the device sufficient to cause a headwave, with all of the attendant problems associated with headwaves in oil containment boom practice. Typical densimetric Froude number relationships for predicting headwave instability were shown to apply to energy dissipation devices as well as to free slicks.

The simple theory predicts that oils of even relatively low viscosity (say 10 cs or more) will thicken in appreciably less distance than water; therefore, the design fiber length is based on slowing only the water phase to 0 fps. However, a review of the Stage I data indicated that thickening of the oil did not begin until the water velocity had been slowed to approximately 1 foot per second. Judging from the somewhat mixed condition of the oil entering the model, this could mean that inertial forces dominated the flow pattern as the oil-in-water mixture progressed through the fibers, until finally the viscous forces began to dominate and the oil-fiber

interaction caused the oil phase to slow down and thicken.

A phenomenon of this sort would be expected to be characterized by a critical Reynolds number, indicating the ratio of inertial forces to viscous forces where viscous forces would begin to dominate. As the oil viscosities in the Stage I tests ranged from 5 to 700 cs, use of a pure oil viscosity in the Reynolds number would not be consistant with observations because the critical velocity was nearly the same no matter what the oil viscosity was. However, treating the incoming top fluid layer as an oil-in-water dispersion, which typically has a viscosity much closer to the continuous (water) phase than the dispersed (oil) phase[3], the concept of such a critical Reynolds number is reasonable. This would also infer that the fiber size and spacing (as part of the characteristic length term, d_e, in the Reynolds number) could be adjusted to control the velocity at which oil thickening could begin.

Another way of looking at the thickening data is that if a headwave tended to form early in the device, the high water velocity at that point would not permit its buildup, and not until the water had slowed to about 1 foot per second would the oil headwave take on its characteristic shape. This would infer that a finite thickness of oil existed at the surface and that severe headwave breakdown and entrainment would carry the oil droplets into the low velocity region of the fibers where coalescing and thickening could occur. The limit is the situation described previously where the whole oil phase is dispersed into the water, and densimetric Froude number relationships do not hold. The headwave that finally took shape at a water velocity in the order of 1 foot per second would be expected to be fairly stable.

The entrainment droplets that occur from headwave instability are subjected to high inertial forces, which tend to break them down into even smaller droplets. When a

sufficiently small diameter is reached the interfacial tension forces will begin to dominate the inertial forces, and the drop size will become stable. Wicks[4] showed that the maximum stable droplet size occurs at a Weber number of 22, as shown in Equation 1.

$$We_c = \frac{\rho_w U_c^2 d}{\sigma} = 22 \qquad (1)$$

where : ρ_w = Density of water

U_c = Water velocity above which no drops exist of diameter d or larger

d = Droplet diameter

σ = Interfacial tension

In the fiber array, where such droplets are assumed to form, the water leaving the device will carry the droplets with it, unless the droplets are large enough, and their terminal rise velocity is higher than the downward water velocity. Because the vertical water velocity component increases towards the bottom, the only chance a droplet has to stay in the device is to impinge on a fiber, where it can then coalesce with other droplets and be dragged to the back of the device by the stronger horizontal velocity components. The chance of a droplet staying in the device then depends on the probability of encountering a fiber; this probability diminishes as the ratio of the drop size to the fiber spacing decreases, and also as the residence time in the array decreases. Also, as droplets become smaller, their surface forces become greater, and they are not as likely to coalesce on a fiber.

The drop size to fiber spacing ratio can be controlled by spacing the fibers closer together. However, this leads to a much denser and shorter fiber array, with even stronger vertical velocity components in it. To maintain a relatively

long fiber array with the smaller fiber spacing, the fiber diameter can then be decreased. Reduction of the fiber diameter and spacing are both limited by practical considerations (fiber support bar size and strength,and fiber strength), and therefore a basic limitation of the fiber concept may exist; as velocities increase, entrainment losses may become dominating, even with the fiber length sized properly. A possible way around this problem is discussed in Section 4.

In the model used during Stage I testing, the ratio of stable droplet diameter (as defined by Equation 1) to fiber spacing was approximately 1:25 at 7 fps inlet velocity. These tests showed the throughput efficiencies falling off around this speed, indicating that the above ratio may have been limiting (the fiber length was designed for a 10-fps velocity). It was felt that by going to a significantly smaller ratio in the large-scale model design, losses would become heavier even with the proper length fibers. Choosing 0.015-inch diameter nylon fibers as the smallest practical fiber size (15-pound breaking strength), 1/8-inch thick fiber support bars as the thinnest practical section, and a 1:25 droplet diameter to fiber spacing ratio, a design speed of 8 fps was therefore set.

As no model test basin is capable of test speeds much higher than 10 fps (OHMSETT), the possible limitation discussed above could not be tested extensively. A possible test program would be to artificially lower the interfacial tension to see if entrainment-limiting speeds (less than 8 fps) could be determined for cases where the fiber length was theoretically more than adequate.

<u>Belt Mechanism</u>: As demonstrated by Stage I testing, the region of maximum oil thickening in the fiber box is dependent on the relative water speed and incoming oil viscosity.

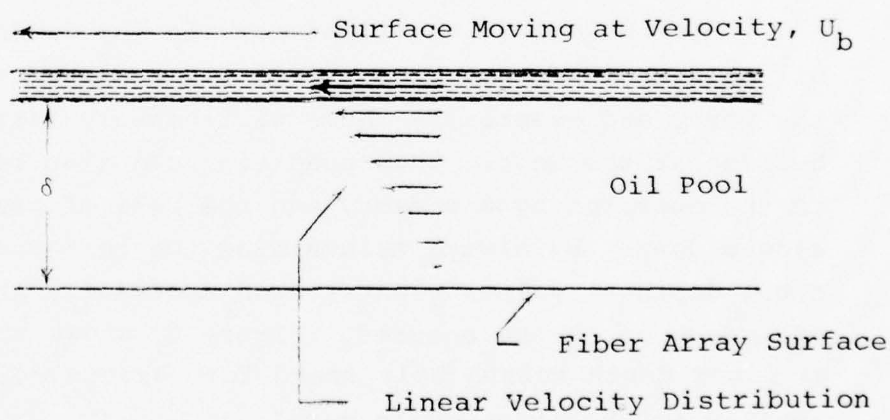
This region moves forward as the relative water speed decreases or as the oil viscosity increases. (The 1-fps water velocity discussed previously is where the thickening starts to occur; viscous oils then thicken faster than light oils, showing up as a shift forward in the maximum thickening point.) Practically, this region of maximum oil thickening should be made to occur at a common collection area somewhere in the device, so that efficient recovery of the oil can be performed. To ensure recovery at all speeds, the obvious place for the collection point is in the rear of the device.

Light oil, once it has been slowed, easily distributes itself in a thick layer extending from the thickening point to the back of the device; the fibers present very little resistance to flow for a low viscosity oil. However, a viscous oil does not flow readily through the fibers and can continue to thicken in one spot until it runs out the bottom, particularly at low speeds. Stage I testing showed that even by placing a suction hose directly into the thickened region, recovery efficiency was poor, because water could be more easily sucked through the fibers than the oil could.

In this program, small-scale model testing showed that by lowering the fibers below the surface (at low speeds) the incoming oil could be slowed and thickened merely by running into and mixing with a pool of oil already established in the device. The incoming water in the layer, or jet, of fluid above the fibers goes under the oil pool and into the fiber array where its kinetic energy is then dissipated (assuming there is enough fiber length left to do this, which there easily could be at low speed operation). In many cases the momentum of the incoming oil was sufficient to cause the layer of oil above the fibers to flow to the back and over a collection weir. The only flow restriction in this case was the viscous shear at the top layer of fibers and the model walls.

A mathematical model of the process was developed, which predicted the distance the oil would flow before critical flow was reached. This model showed that at actual flow paths less than this critical distance the oil could flow over a weir at the same rate it entered the device; at distances greater than this, the incoming rate of oil could not be maintained all the way to the weir, and presumably it would thicken ahead of the weir and run out the bottom. The critical distance was a function of the oil viscosity, velocity, and depth of fibers. A static layer of oil was presumed to exist within the fiber array and did not enter into the flow pattern.

Because of the uncertainty in knowing whether the fibers were set low enough, it was decided to provide a more positive means of assisting the flow to the weir area. Several secondary oil transport systems were then investigated for assisting the oil flow. Based on the results of flume testing, the most simple and effective concept was to drag a solid surface over the top of the oil pool from front to back, setting up a velocity distribution in the oil similar to that shown in the sketch below:



For the moving solid surface, a smooth-surfaced endless belt was used, which was operated with enough slack to conform to the oil surface, but which also tended to plane on the surface so that a nearly constant separation, δ, was maintained.

This separation was also the approximate depth that the fibers were lowered below the surface.

Assuming that the fiber array surface acts as a second stationary surface, the average velocity in the oil is then $U_b/2$, and the volumetric rate of oil flow can be determined from Equation 2.

$$Q = \frac{U_b \delta w}{2} \qquad (2)$$

where: Q = Volumetric oil flow rate

U_b = Belt velocity

w = Belt width

If, for a given belt speed, the flow rate equals or exceeds the incoming flow rate, then all of the oil buildup will occur in the rear of the device in front of the weir. If pumping is not fast enough the oil will thicken in front of the weir, where an interface sensor can be placed to indicate an overfilling condition, signaling the operator to speed up pumping.

If the oil in the fiber-to-belt gap is depleted, the oil being held in the fibers will float upward to fill in the void, and eventually there will be very little oil buildup at the weir. This condition can also be signaled to the operator by a sensor, and the rate of pumping can be slowed down. By always maintaining the belt speed and/or fiber depth at values greater than necessary, then adequate oil recovery can be ensured. Figure 3 shows theoretical curves of fiber depth versus belt speed for various oil flow rates, as applied to the large-scale model.

The fibers should be maintained at less than 4 inches below the surface, as flume testing showed

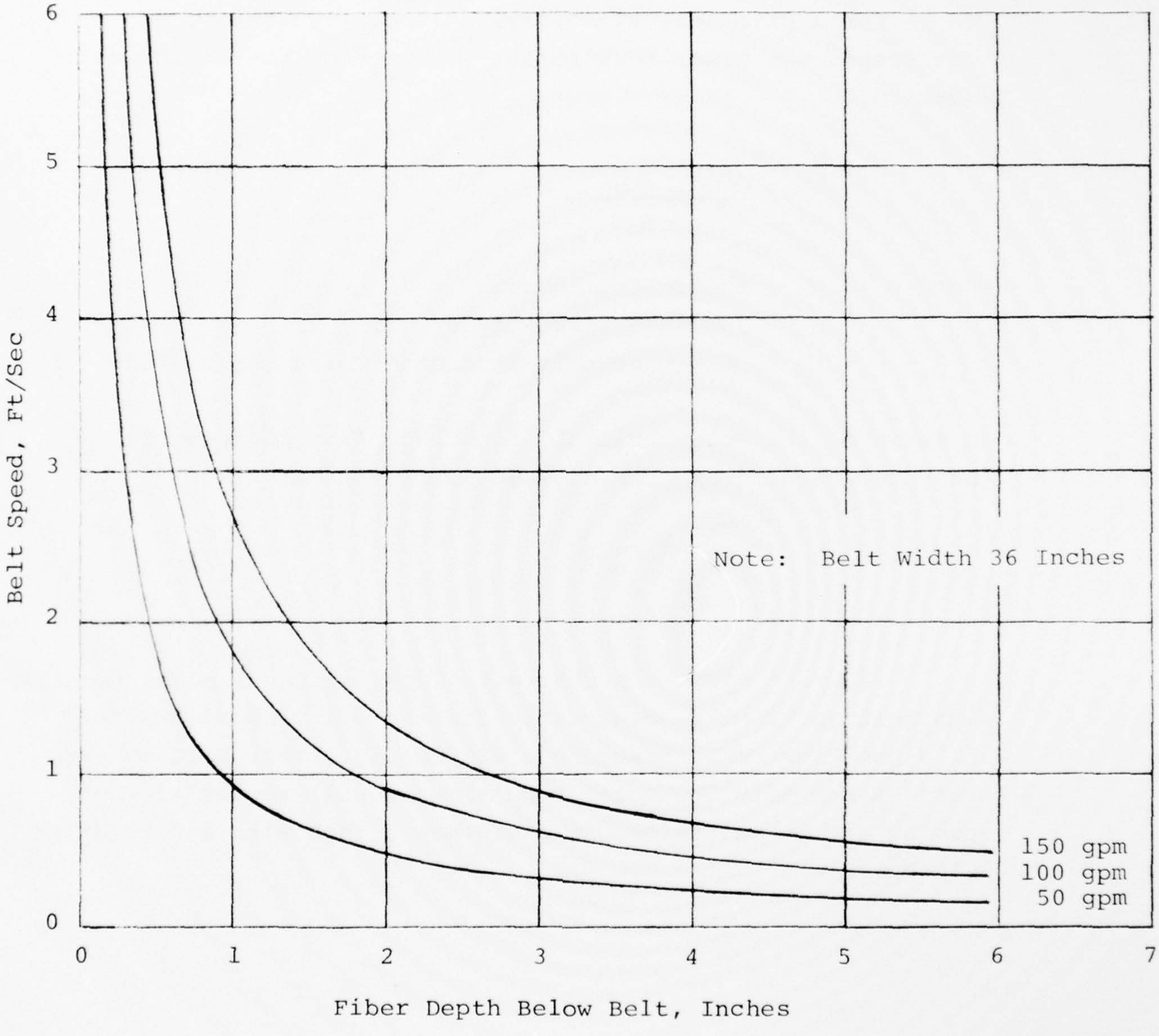


FIGURE 3. BELT SPEED VS FIBER DEPTH, THEORETICAL CURVES

that considerable mixing of the incoming oil and water can occur at more than 4 inches separation. In fact, the smaller the separation the better, as long as sufficient belt speed and power can be maintained. A belt velocity of 2-3 fps was shown to perform well in the flume tests.

For a given oil viscosity, belt configuration, and belt speed, the power requirement is given by the following equation:

$$P = \frac{\mu U_b^2 L_b w}{\delta} \tag{3}$$

where: P = theoretical power

μ = absolute viscosity of oil

L_b = length of belt in contact with the surface

In terms of the volumetric oil flow rate from Equation 2, the power requirement can also be expressed as:

$$P = \frac{4\mu Q^2 L_b}{\delta^3 w} \tag{4}$$

Figure 4 shows the theoretical variation of power requirement with belt to fiber spacing ratio for two oil viscosities and a 150-gpm flow rate, assuming a 10-foot by 3-foot belt contact area. Reasonably low power requirements will result if the spacing can be maintained at a minimum 1 inch with a 2 to 3-fps belt speed.

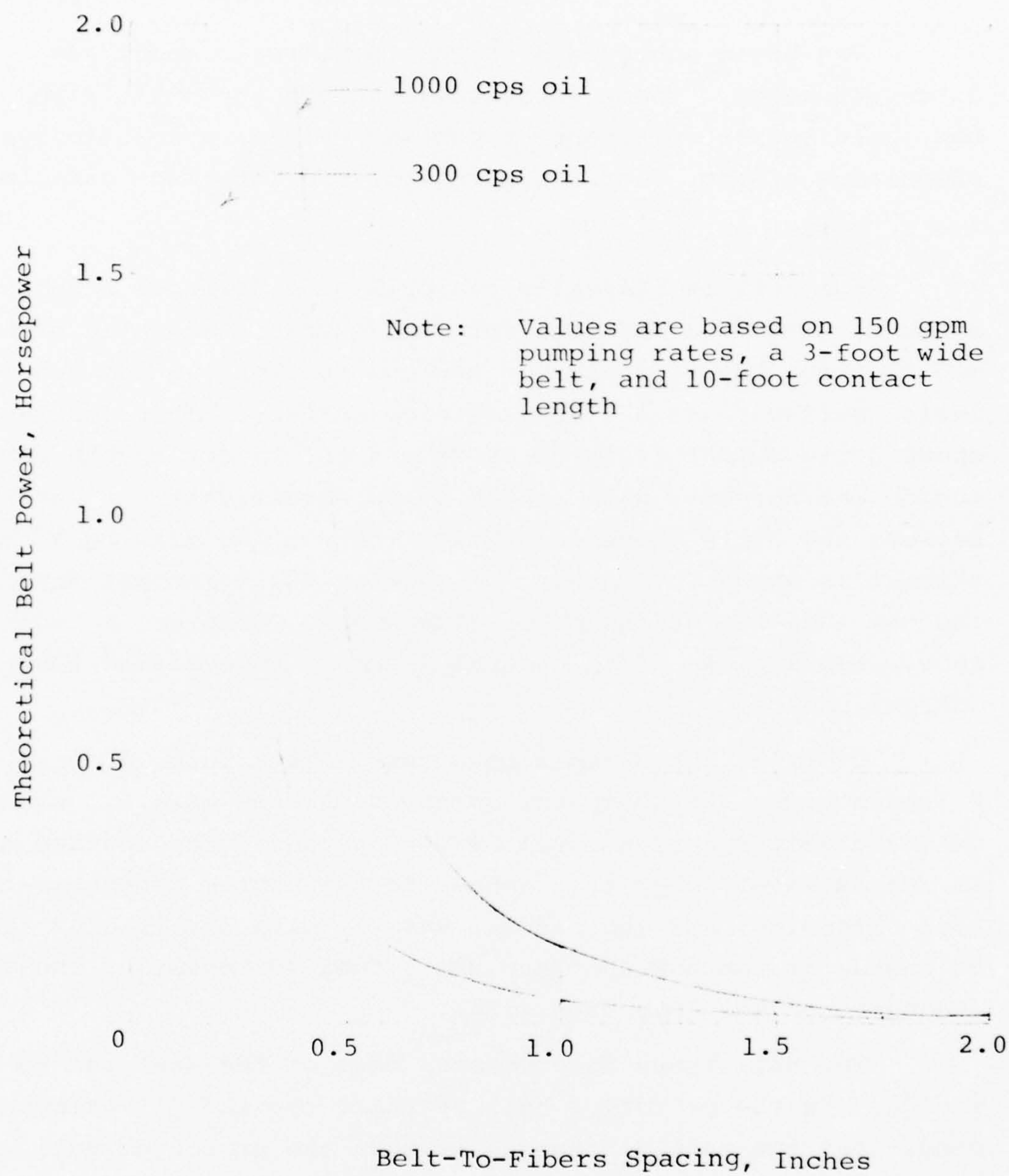


FIGURE 4. BELT-TO-FIBERS SPACING VS BELT POWER, THEORETICAL CURVES

3.3 Basic Subsystems of Large-Scale Model

The basic subsystems of the large-scale model are discussed below. These subsystems include the hull, fiber box, belt mechanism, transfer pumping system, hydraulic system, propulsion system, debris protection, and interface detectors.

3.3.1 Hull

The hull is basically the hull of a Spiltrol Harbor Skimmer, which was modified for fast-current use. The principal modification was to construct new bow sections, which had flat inside surfaces and a flared outside surface. This design was shown during model tests to provide a relatively smooth flow inside the skimmer, with little or no significant bow wave between the hulls (Section 3.5.2). An outline drawing of the skimmer is shown in Figure 2, showing the principal dimensions and the location of the major components. Figures 5 and 6 show various views of the actual skimmer, as modified for fast current use.

Overall, the skimmer measures 32 feet long, 10 feet 8 inches wide, and 10 feet 2 inches high, and with all equipment on board weighs approximately 17,000 pounds. The average draft is approximately 2 feet 7 inches (to the bottom of the 12-inch keel extension) and the natural trim is with drafts of 2 feet 3½ inches at the bow shoulder and 2 feet 10 inches at the stern (measured on the starboard side).

The hull shape incorporates most of the features to be included in the prototype hull at least for the oil skimming condition; the main difference is that the prototype hull would be a full catamaran for minimum resistance during high-speed transit, whereas the test skimmer hull has the aft one third constructed as a full-displacement hull section. However, performance differences in the oil skimming mode are not expected to be significant.

FIGURE 5
TEST SKIMMER HULL BEFORE OUTFITTING

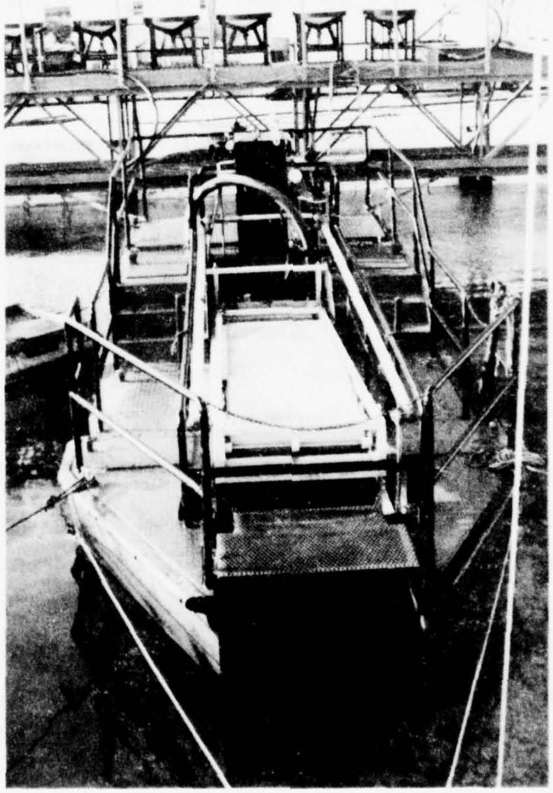


FIGURE 6
TEST SKIMMER PREPARED FOR RUN

The stern section of the hull contains the equipment listed below. Access to each compartment is through a hinged cover.

- Starboard: Transfer pump and motor, 3-way valves, piping, and bilge pump.
- Middle: Engine, stern-drive, hydraulic pump, much of the hydraulic valving and controls, and access to the control console.
- Port: Hydraulic reservoir and fuel tank.

The port and starboard hull sections forward of the stern section are mirror images of each other. Adjacent to the stern section is an oil storage tank. Forward of that tank is a ballast chamber, and next is the trim tank in the bow section. Access to each compartment is through a 20-inch square manway with a cover bolted to the deck. Each compartment also has a drain plug in the bottom.

Along the bottom inside edges of each hull section runs a longitudinal beam, which extends 12 inches below the keel plate. This acts as a shroud around the fiber box when it is in its lowest position; it also protects the keel plate during shipping and handling.

The bow is raised higher than the main deck to minimize wash-over during wave tests. There is also a hinged cross-walk between the two hull sections.

A 2-inch pipe with a slot down its length is welded vertically into the inside surface of each bow section. These slots were used during testing to hold a vinyl fabric dam, constructed with lengths of 1½-inch pipe at each edge which could be slipped down into the 2-inch pipe sections with the fabric extending out of the slots to cover the front of the skimmer. Another use for the pipe slots would be to hold the ends of an

oil boom used for diverting oil into the skimmer, or for holding adapter plates to which diverting booms were attached. During tests, plain 1½-inch pipe sections were inserted into the 2-inch pipes to prevent vortexing. Figure 6 shows the fabric dam in place in the slots.

The fiber box fits into a recess along the inside surface of each hull, so that a smooth flow of water into the fibers will occur. The forward jacking screws (Section 3.3.2) are enclosed by sheet metal shrouds, which are welded to the hull at the forward edges, and which slightly overlap the inside box surface.

Hull construction is of steel, coated with inorganic zinc primer and top coats of epoxy ester and alkyd paints. A control console houses the steering wheel, engine instruments (tachometer, battery charge, oil pressure, water temperature, hour meter), hydraulic controls and gauges, interface indicators, headlamps, throttle, on/off controls, bilge pump switch, spotlight, and running lights (Figure 7). A stern light is also provided. Steel pipe railings are installed around the outer and inner sides of the deck. Rubber fenders around the outside provide additional protection.

3.3.2 Fiber Box

A drawing showing the main features of the fiber box is shown as Figure 8 . The various parts are described below.

The fibers are 0.015-inch diameter nylon monofilaments, having a 15-pound breaking strength. They are supported by being continuously wound around two 24-inch long by 1 x 1/8-inch vertical stainless steel bars spaced 15 feet apart, at a nominal fiber spacing of 0.145 inches along the bar. Each bar is then covered on its leading edge with a Buna-N rubber extrusion and adhesive, which provides a streamlined shape to the bar and secures the fibers in place. Construction of an individual fiber support bar is shown in the sketch below; front and rear supports

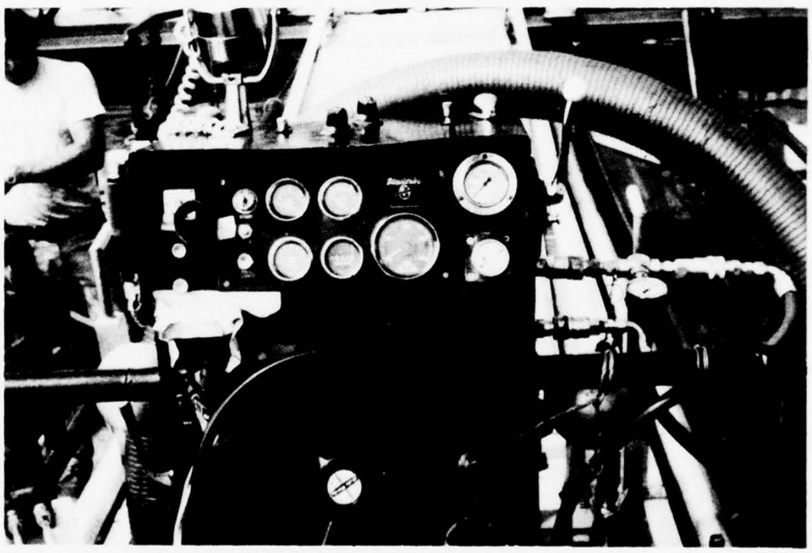


FIGURE 7
CONTROL CONSOLE

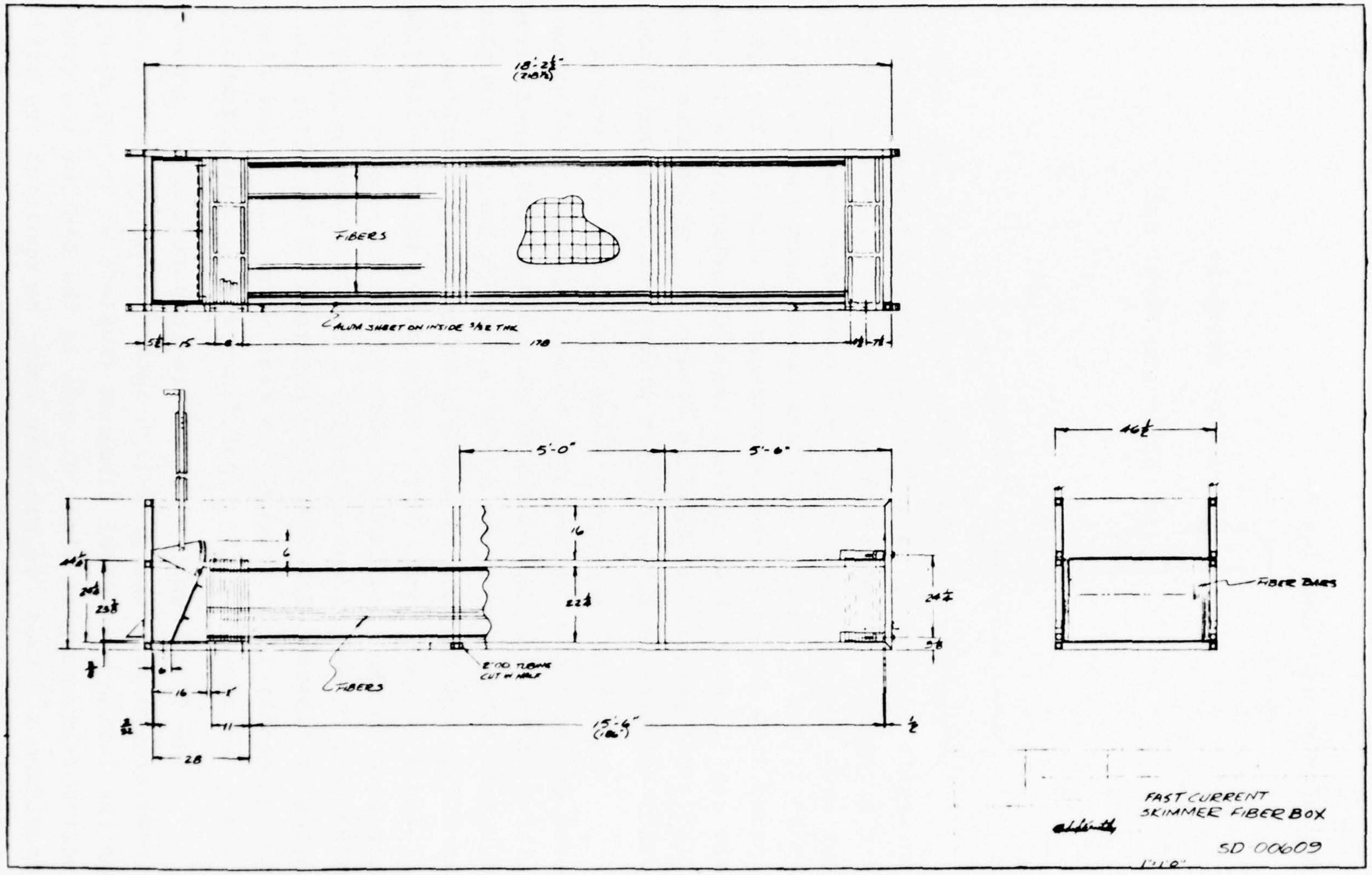
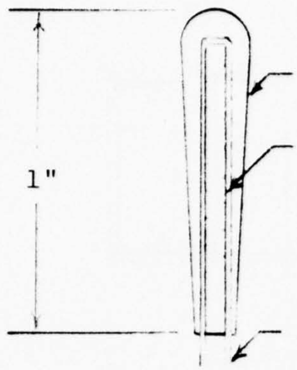


FIGURE 8
MAIN FEATURES OF FIBER BOX

are constructed identically.



To provide a uniform fiber spacing of 0.145 inches horizontally as well as vertically, the fiber support bars are arranged in a matrix on approximately 0.290-inch centers, but in a staggered pattern of six rows, each row being 2 inches apart (front to back). The bars within each row are then spaced 1.74 inches apart. Advantages of this spacing system are that flow blockage is kept low and installation is simplified. The pattern is shown in Figure 9 , which also shows other features of fiber support plates, as described below.

Each fiber support bar has two square nuts welded to each end of it, which are used to bolt the bar to aluminum plates at the top and bottom of each end of the fiber array. The area between each row of fiber support bars on the plates is milled out as much as possible to permit the vertical flow of fluid in wave conditions. There are a total of 144 fiber bar sets in the total array, each containing approximately 4980 feet of continuous fiber for a total of approximately 136 miles of fibers. The overall dimensions of the array are approximately 10 feet long, 3.5 feet wide, and 2 feet high. Figure 10 shows the top front fiber support plate installed.

The fiber support plates are supported by a three-sided framework constructed of 2-inch square aluminum tubing, covered on the inside with sheet aluminum (6061-T6). In the rear, the bottom fiber support plate extends to the back of the framework, providing a bottom for the weir sump; no openings are milled into this particular plate. The top rear fiber support plate

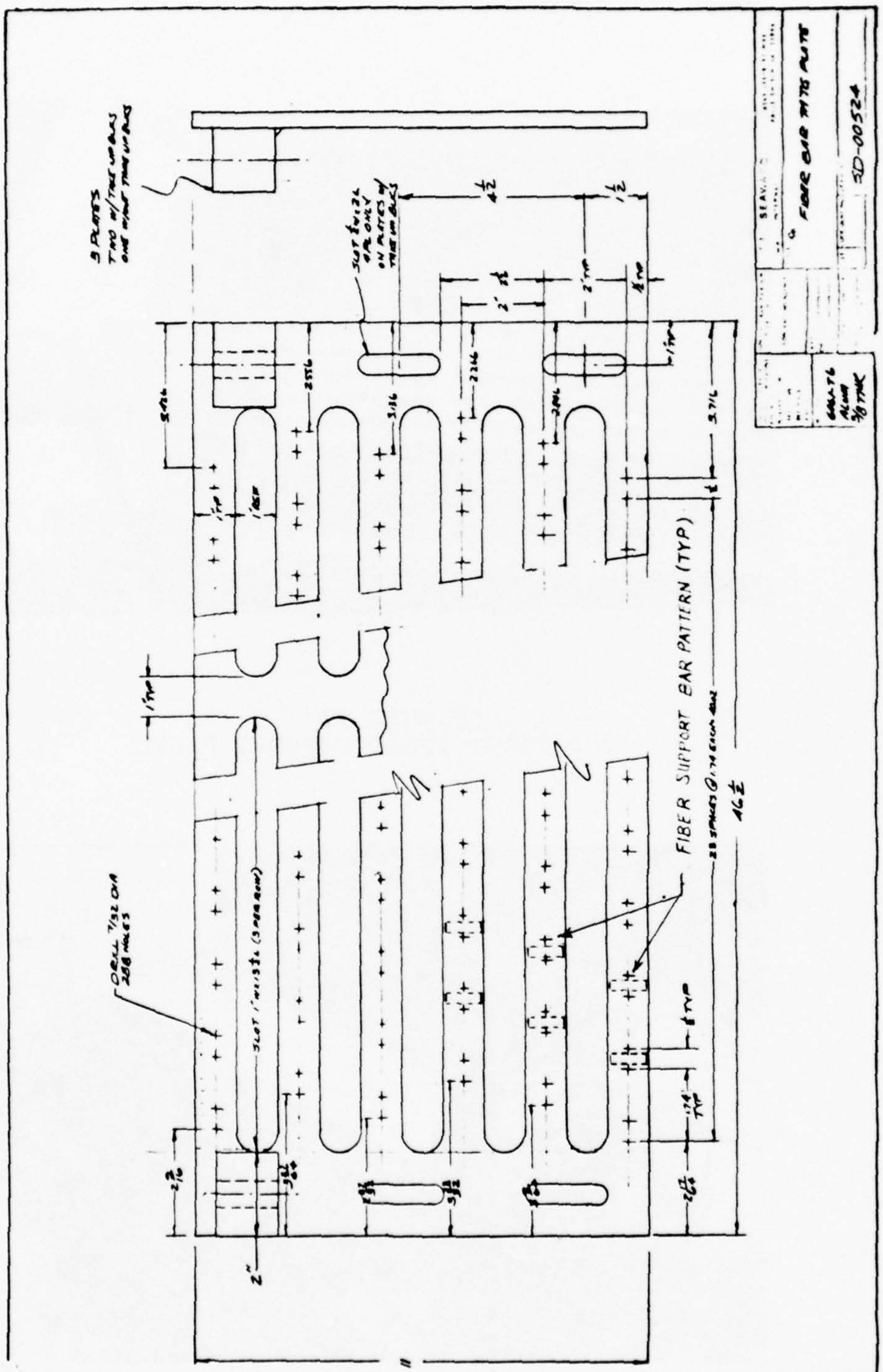


FIGURE 9
FIBER BOX FEATURES

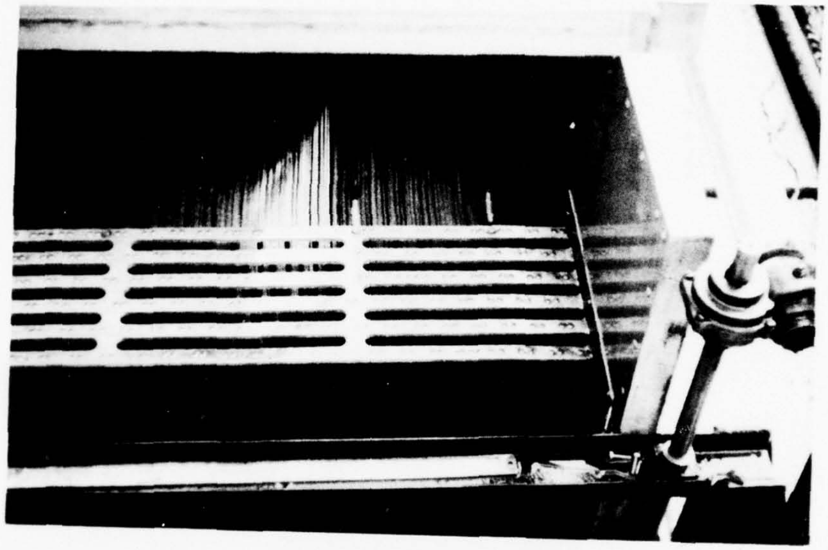


FIGURE 10
TOP FRONT FIBER SUPPORT PLATE

FIGURE 11
FIBER BOX IN ELEVATED POSITION

is bolted to the framework. In the front both the top and bottom fiber support plates have adjustment screws for changing the tension in the fibers during assembly. The framework construction and tensioning screws can be seen in Figure 11.

The framework, or fiber box, also has strength members across the bottom in three places. These, together with the fiber support plates, provide all of the stiffening required. The front and top of the framework are completely open, but the bottom is covered with a coarse, 3-inch mesh stainless steel screen, to provide some protection for the fibers along the bottom. In the rear, behind the fibers, is a sump with adjustable weir (Figure 12); recovered oil is pumped out of the sump through a 4-inch connection and hose in the back. The box sides extend approximately 18 inches above the fibers to contain waves, and to permit lowering the entire box further into the water for recovery of viscous oils at lower speeds.

To raise and lower the fiber box, a system of stainless steel, 1-inch, Acme-thread jack screws is used, with one screw located at each corner of the box. The screws are approximately 84 inches long overall, and are suspended from thrust bearings located above deck level. Plain radial bearings are used at the bottom of the screws (located near the bottom of the skimmer) to keep the screws vertical. The fiber box is bolted to the four mating Acme nuts, so that by turning all four screws simultaneously, the nuts (and therefore the fiber box) translate vertically. To ensure that all of the screws turn simultaneously, a system of right-angle gear boxes and interconnecting drive shafts (2½-inch aluminum pipe) is used; one hydraulic motor coupled to one of the screws thus causes all four screws to turn at once. The box can be elevated from the bottom of the skimmer to approximately 4.5 feet above the bottom. The drive shafts, gear boxes, screws, and drive motor can be seen in Figure 13.

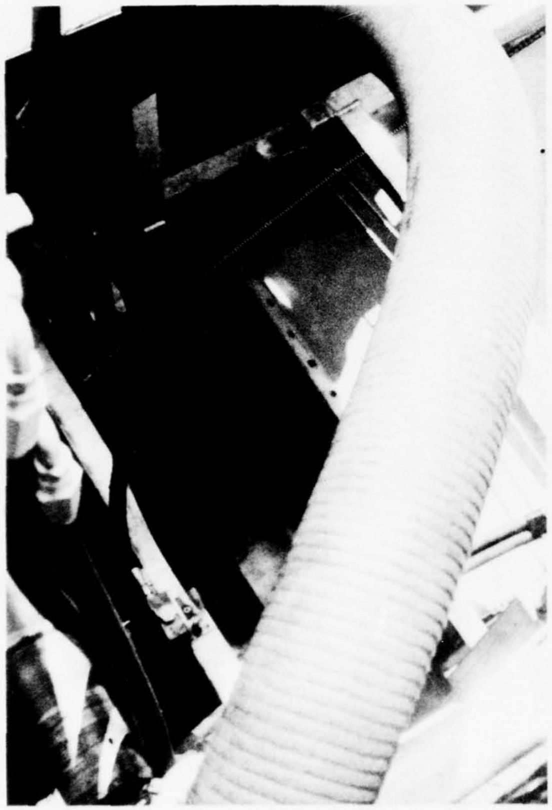


FIGURE 12
OIL SUMP WITH ADJUSTABLE WEIR

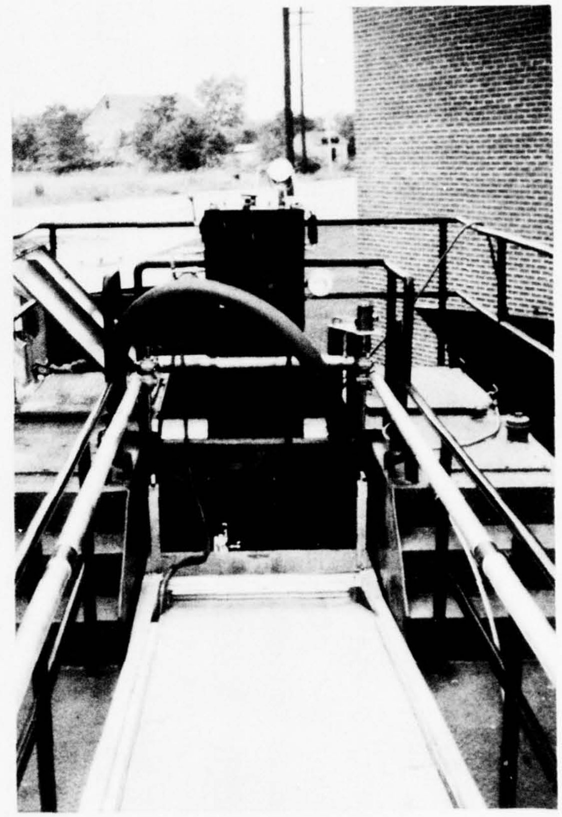


FIGURE 13
FIBER BOX ELEVATING MECHANISM
FEATURES

3.3.3 Belt Mechanism

A drawing showing the overall layout of the belt mechanism is shown as Figure 14.

The conveyor-type belt is a Goodyear Chemivic, 2-ply, polyester-reinforced, PVC-Nitrile rubber belting, 5/32-inch thick. As can be seen, the belt hangs down slack on the surface of the water and has a positive drive mechanism on the forward roller. This allows the belt to conform to incoming waves at the entrance region of the fiber box and is necessary to prevent severe turbulence and oil-water mixing where the wave crests first contact the belt. Aircraft cables were strung between the top fiber support plates in order to keep most of the weight of the belt and roller chain off of the fibers, thus minimizing wear on the fibers.

In order to ensure positive drive and tracking of the conveyor belt, stainless steel roller chains are fastened to both edges of the belt, which is thus driven by sprockets on the forward drive roller. The drive chains are #40 stainless steel roller chain with single attachment points every 6 inches. In order to ensure proper spacing while bending over a radius, the links are rivetted to the belt, using washers as spacers between the chain links and belt.

Proper side-to-side and lengthwise spacing and matching of the drive chains are critical and caused some initial difficulty in fabrication. The sprockets on the forward drive roller are spaced away from the roller to provide clearance space for the attachment tabs and can be adjusted laterally and radially for proper tracking of the system. Nylon snubber rollers are provided to ensure meshing and prevent the chains from jumping off the sprockets (See Figures 15 and 16).

After initial tuning and adjustment of the drive system, the belt tracked smoothly during testing. The forward drive

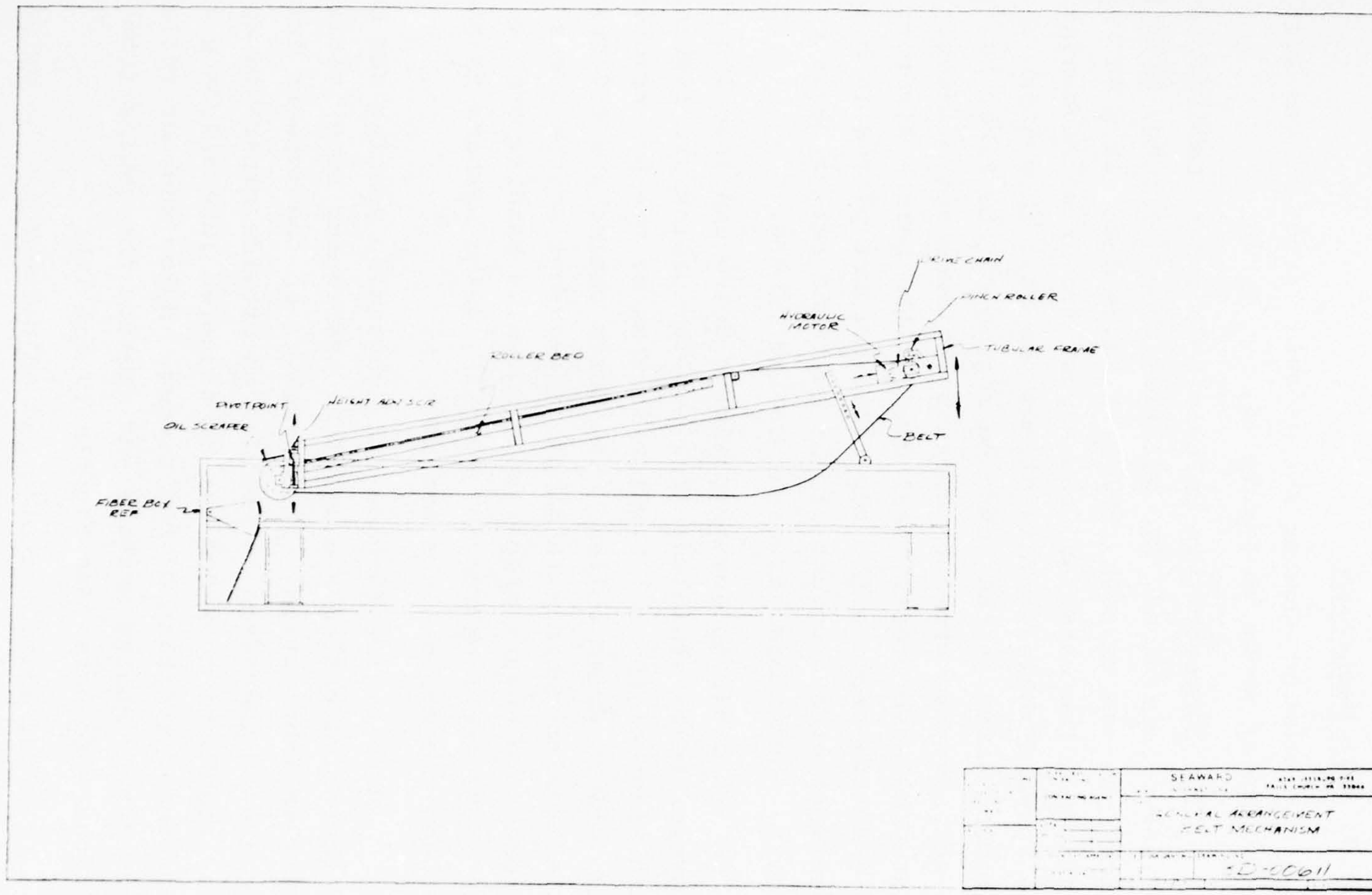


FIGURE 14. GENERAL ARRANGEMENT OF BELT MECHANISM

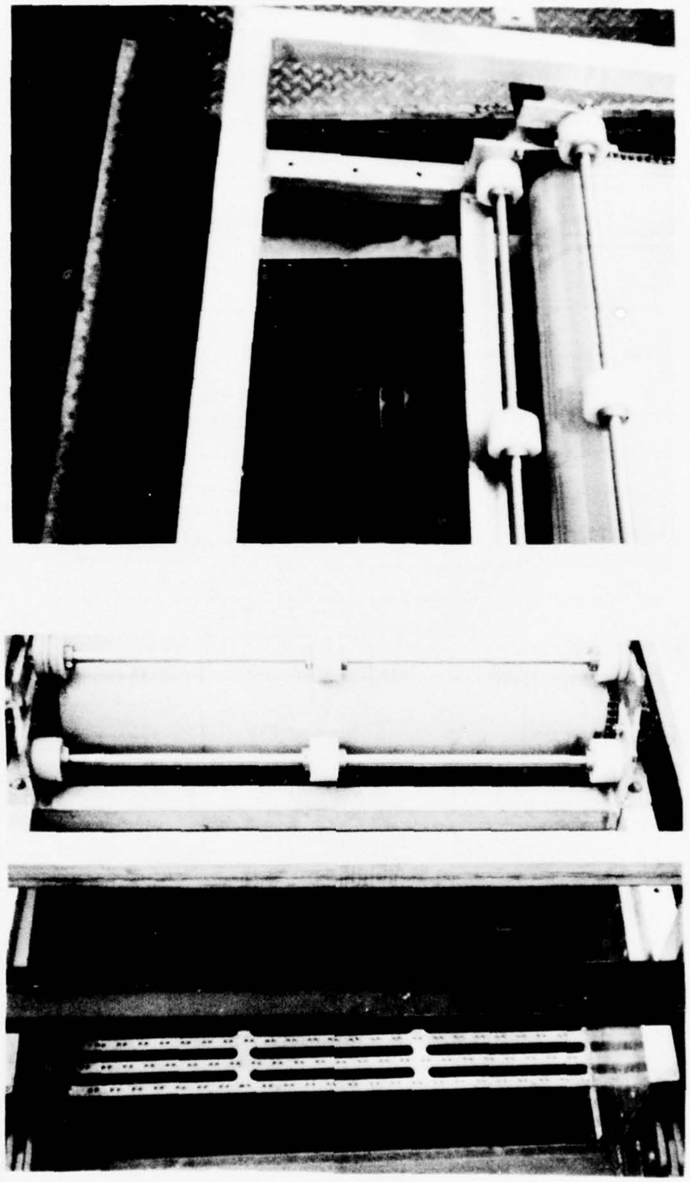


FIGURE 15. FRONT END OF FULL-SCALE BELT SYSTEM

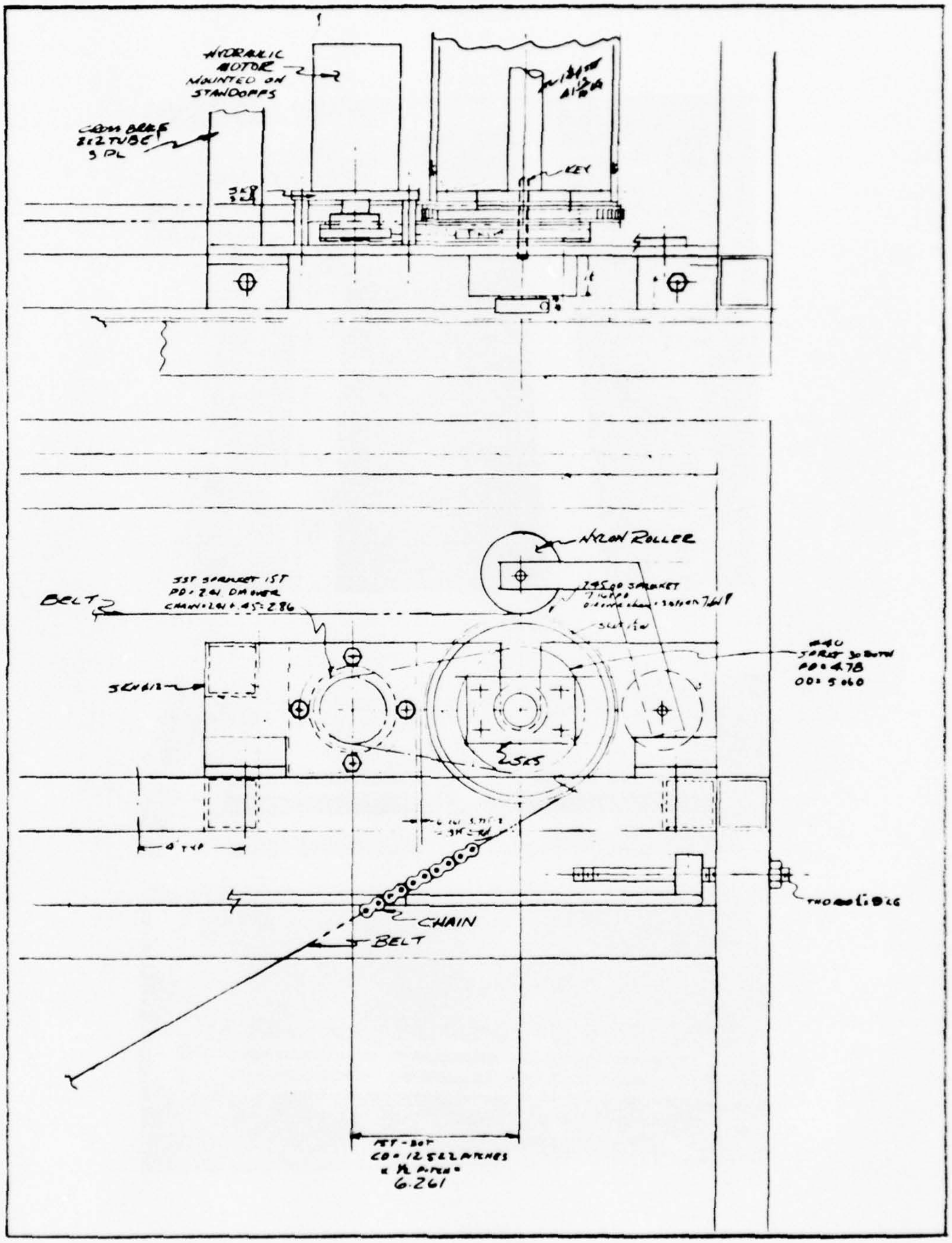


FIGURE 16. BELT DRIVE MECHANISM

roller is driven by a geroter-type hydraulic motor through a chain drive. Belt speed can be controlled through a shutoff and flow control valve on the operator's control console. Nominal belt speeds used during testing ranged from 1.5 fps to 3 fps. This range of operating speeds was chosen based on operation of a similar system during small-scale flume testing.

In order to prevent severe speed oscillation or "bucking" in the belt system, it is necessary that the belt be supported over most of its length on the return or top side of the system. Initially this was done with small idler rollers and a flat plate slide bed. This slide plate was later replaced with a slide system of small rollers in order to reduce frictional drag with viscous oils.

The rear roller serves only to keep the belt tensioned and tracking properly, providing no driving force. The chains ride directly on the roller, which extends the full width of the belt and is coated with a urethane elastomer. Side plate flanges serve to keep the belt centered on the roller.

A weighted oil-resistant squeegee pivots from the rear frame member, bearing against the moving surface of the belt. This scrapes the belt free of oil, which drips into the weir sump collection area. Being free to pivot, the squeegee scraper can tolerate slight clinging debris and irregularities, such as the belt lacing, without jamming.

At the rear roller bearing blocks, a chain-connected screw mechanism allows for vertical adjustment of the rear roller (See Figure 17). This permits the height of the rear roller to be adjusted to match the water level within the fiber box. Although this mechanism is useful for test purposes, it appears from testing that this would not be necessary for field use of the skimmer. At the forward end of the device, the entire belt system can be adjusted up or down to allow for different wave conditions; or the drive roller mechanism can be adjusted forward or back to adjust the tension of the belt. The overall

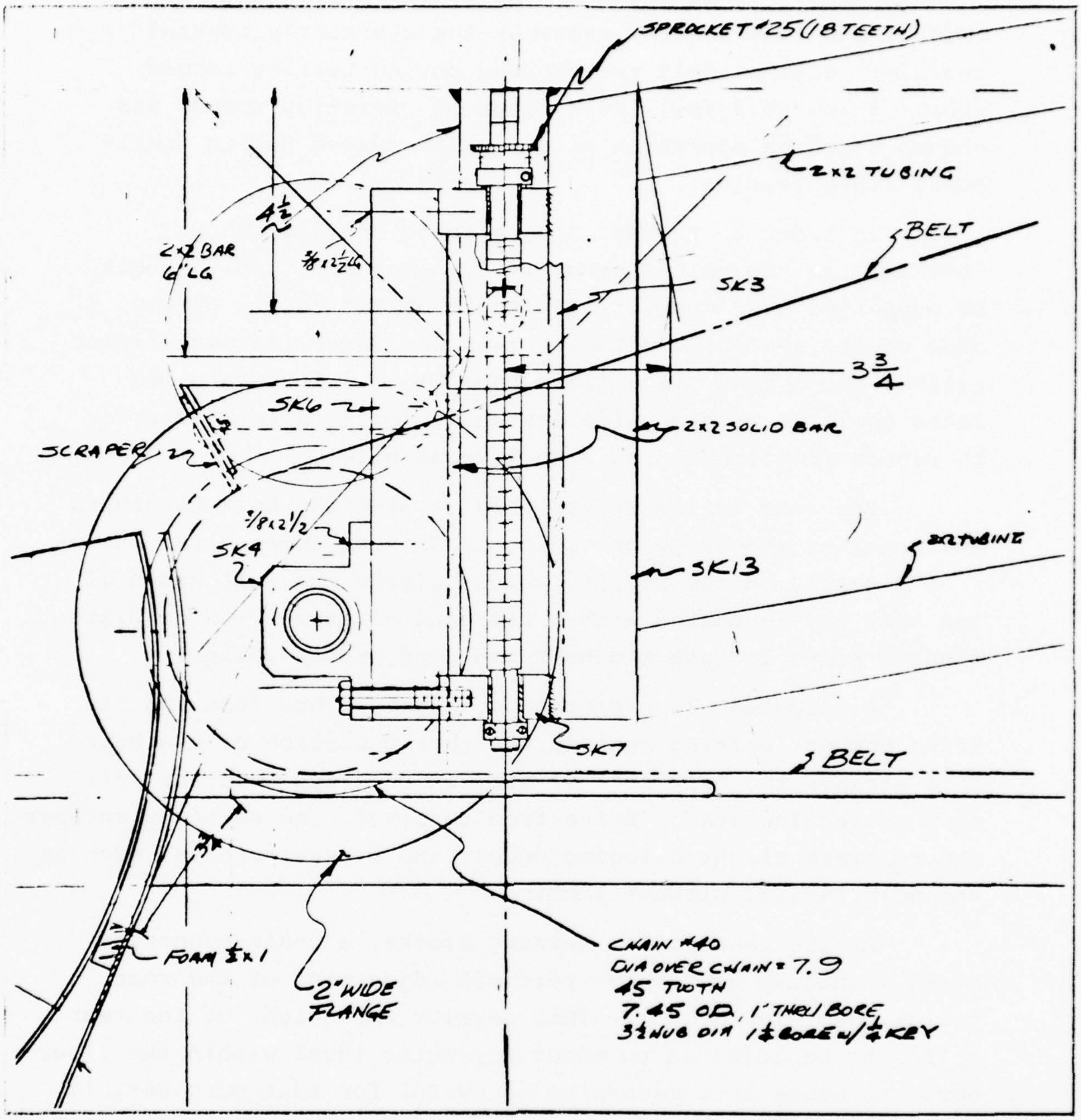


FIGURE 17. BELT SYSTEM REAR ROLLER

dimensions and layout of the belt system are such that it may be folded down and stored in the upper section of the fiber box.

3.3.4 Transfer Pumping System

The transfer pumping system consists of a pump, tank storage within the hulls, and the valving and piping necessary to transfer the oil. A flow schematic is shown in Figure 18.

The pump is a MD Pneumatics model 4540H lobe pump, chosen because of its positive displacement feature and its potential for handling certain types of debris.[5] It was sized to provide 150 gpm of a 10,000-SSU oil when operated at 50 percent of its rated speed. The hydraulic motor has a 6-cubic-inch displacement and was sized to provide the desired transfer flow at a 50-psig discharge pressure.

To minimize the pressure drop in the lines, 4-inch piping was used where possible. With the 3-way DeZurik valves, flow can be pumped from the weir sump to either the hull tanks or the stern outlet, or from the hull tanks to the stern outlet. Figure 19 shows the pump, motor, and valves installed in the starboard compartment.

The hull tanks are piped so that both tanks must be filled simultaneously. The total storage volume is 1144 gallons. Each tank has one full-section baffle to minimize sloshing during operation. An overflow line from each tank extends to the bottom of the tank, permitting some decantation of water to take place if the tanks are filled to capacity. A tall pipe on the top of each tank allows the tank to vent during filling or emptying, without overflowing oil during decanting. The water overflow line is directed back into the inside hull area to capture any oil that may leave with the water.

3.3.5 Hydraulic System

The hydraulic system was designed to operate the recovered oil transfer pump, the belt, and the elevating screws for the

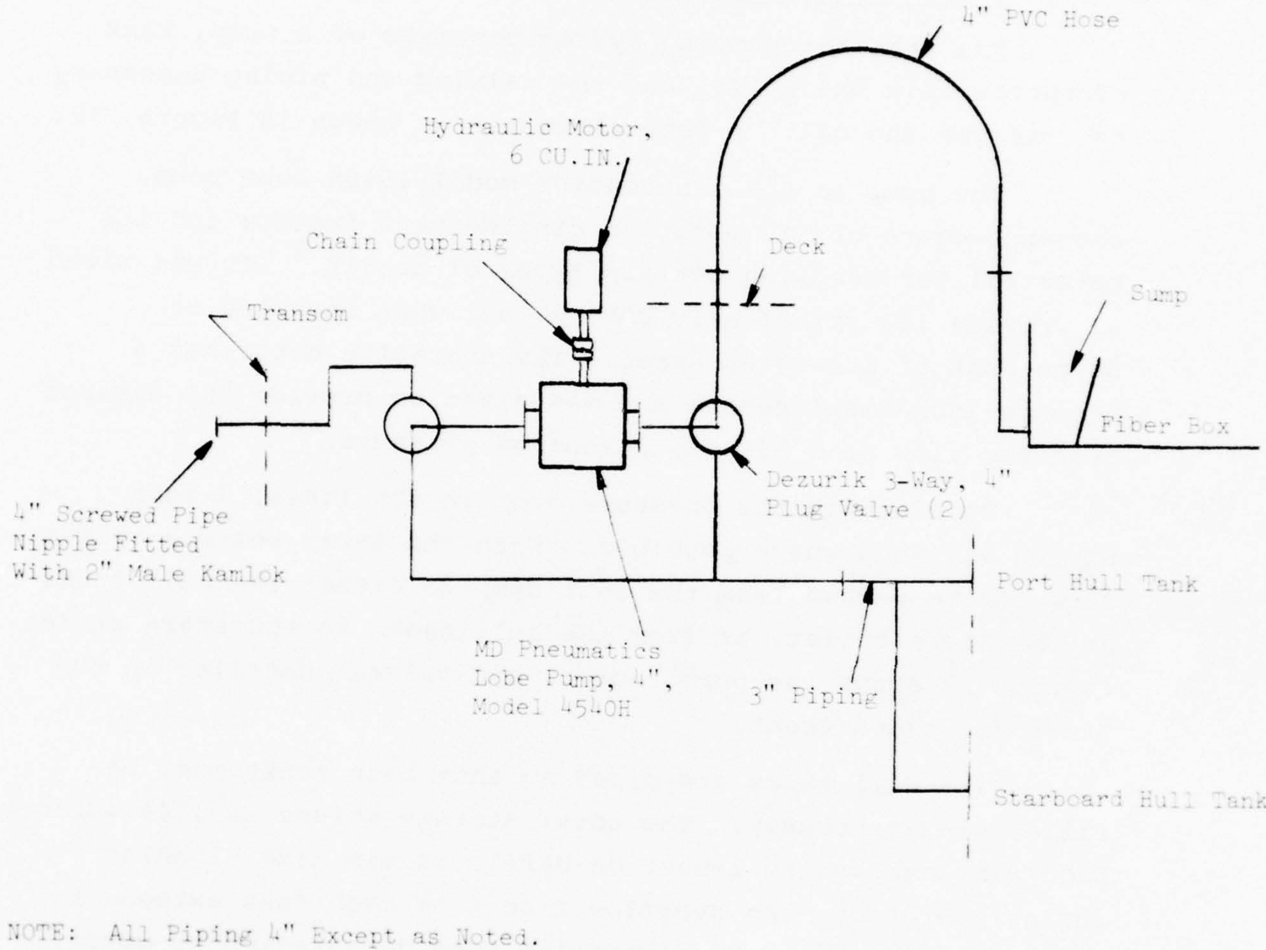


FIGURE 18
TRANSFER PIPING SCHEMATIC

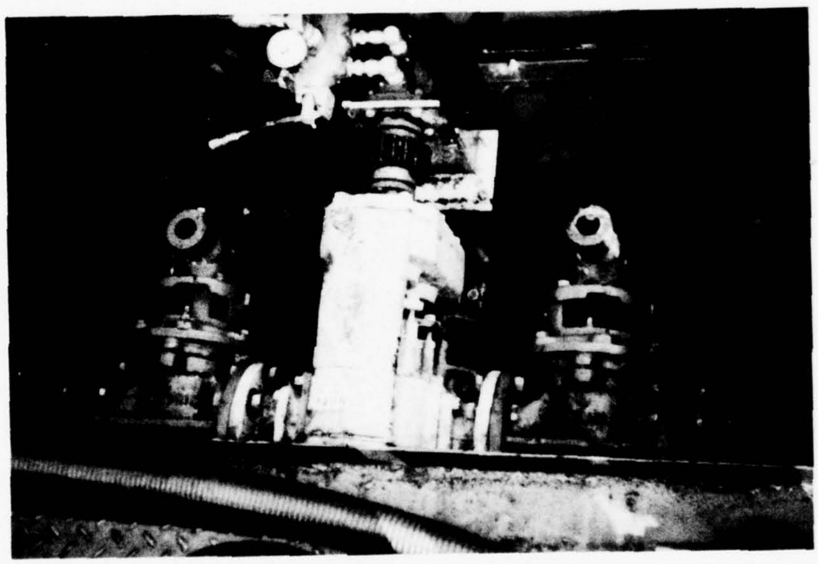


FIGURE 19
TRANSFER PUMP INSTALLED IN SKIMMER

fiber box. A schematic drawing of the system is shown in Figure 20 .

A single variable-volume, pressure-compensated, axial-piston hydraulic pump is used to provide oil for all three circuits. This pump is directly driven by the diesel engine through a coupling attached to the engine raw water pump pulley (normally the fan belt pulley). Being pressure compensated, the pump supplies a constant pressure (adjustable) and only enough flow to satisfy circuit requirements. The pump was sized so that at diesel speeds of 1000 rpm or greater sufficient oil is provided to operate the belt and transfer pump simultaneously at design rates. A remote compensater adjustment was provided, but because of unresolved difficulties with it, compensator pressure adjustments had to be made at the pump itself. A nominal system pressure of 2000 psig is provided.

For the transfer pump, the basic circuit consists of a hydraulic motor and a pressure-compensated flow control valve, with a ball valve for shutoff. The pressure-compensated flow control valve provides a relatively constant flow, which is nearly independent of the load (i.e. transfer pump discharge pressure). The same type of circuit is also used for the belt system. A directional control valve was installed in the transfer pump circuit only to reverse the pump during OHMSETT tests.

For the jack screw system, no flow controller is used, as a constant speed is not necessary. In this case a needle valve is used to regulate flow to the screw motor. A directional control valve is provided to permit raising or lowering the system. To avoid raising or lowering the box too far, a safety circuit is included, which activates when a small directional control valve mounted on the box is actuated by stops attached to the hull. For example, when the box is raised to the upper limit, the valve handle is actuated, venting the pressure from a pilot-operated check valve in the motor supply line, causing the flow to be blocked. The box direction can then be lowered

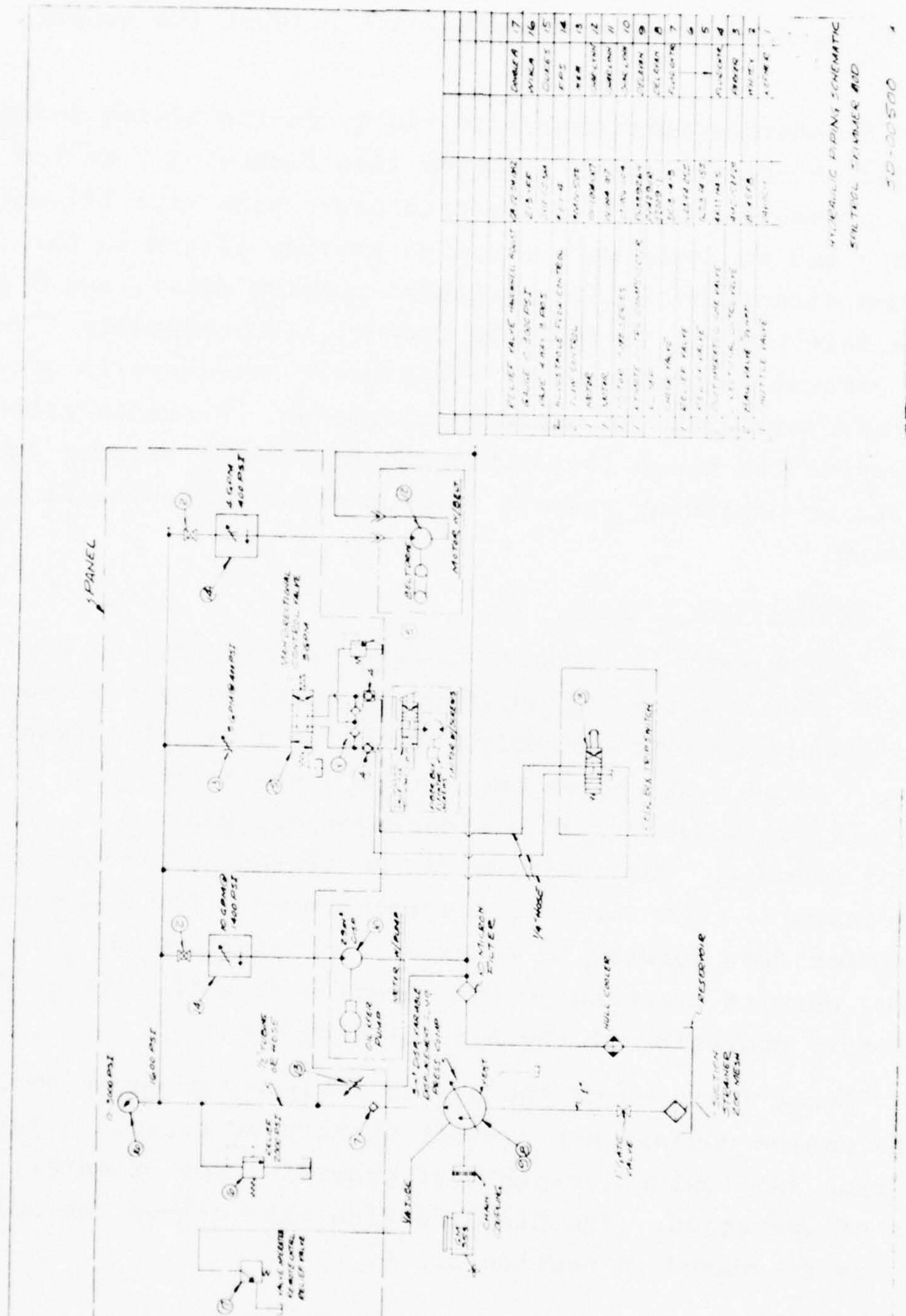


FIGURE 20
HYDRAULIC SCHEMATIC

by reversing the main directional control valve. A separate system-relief valve is always maintained on the high pressure side of the circuit by a shuttle valve between the supply lines.

Standard appurtenances to the hydraulic system include a 30-gallon reservoir, hull cooler (See Figure 5) relief valve, pressure gauges, and suction and return line filters. Plumbing and controls were sized to provide 12 gpm to the transfer pump circuit (for 150 gpm design pumping rate), and 3 gpm to the belt circuit (3-fps belt speed), simultaneously. The screw circuit requirements of 4 gpm would not normally occur simultaneously with the other requirements. A needle valve was provided to bleed fluid through the cooling circuit during long engine operating periods when no other hydraulic flow was occurring.

3.3.6 Propulsion System

The skimmer is capable of being self-propelled at a speed of over 4 knots. Propulsion is provided by a Stewart & Stevenson stern-drive assembly, utilizing a GM 3-53 diesel engine. Rated brake horsepower at 2800 rpm is 115 hp. Side-arm steering is used, with a steering wheel mounted on the control console. The outdrive can be tilted up electrically for transport. The throttle control provides for a smooth transition from forward to reverse. An interlock on the throttle control permits disengaging the outdrive from the diesel for stationary operation of the hydraulic system.

Other features of the system include raw water cooling of the engine coolant and 12-volt battery starting. A 50-gallon fuel tank is provided, capable of providing approximately seven hours of operation. The diesel engine also drives the hydraulic pump, as discussed in Section 3.3.5.

The prop does not extend below the bottom of the hull, and to provide sufficient water to the prop a cut-away stern is provided. The raw water intake is located in the cut-away region; raw water is discharged through the exhaust pipe. Figure 5 shows the outdrive assembly on the skimmer.

3.3.7 Debris Protection

Two types of debris protection are provided for the skimmer. First, to protect against the damaging effects of large debris, a trash gate can be installed on special brackets located on the bows. This gate is constructed of 1-1/2 x 1/4 inch aluminum bars mounted vertically between two cross-pipes. It can be pivoted forward and up to assist in debris removal. Figure 21 shows the trash gate installed on the skimmer.

For smaller debris, a 3½-foot wide by 17½-foot long net is provided. One end of the net is attached to the bottom front fiber support plate and the other end is drawn back over the top of the fibers (beneath the belt) and attached at the top rear fiber support plate. With this arrangement debris that passes over the front fiber support plate (when skimming viscous oils with the fibers lowered) is trapped on top of the fibers, usually where the oil pool forms and velocities are low. With the fibers raised, debris is trapped at the fiber support bars, where the turbulence caused by the debris has a chance to dissipate immediately in the fibers. To clean the debris out of the skimmer,the entire net can be removed and replaced with a fresh one.

In the OHMSETT tests no debris studies were made, and therefore none of the above systems were tested.

3.3.8 Interface Detection

Two types of oil-water interface detectors were used on the skimmer to indicate the oil depth in front of the weir. One was a Delaval float-type indicator, consisting of a 0.97 specific gravity float and a microswitch,which was connected to the engine

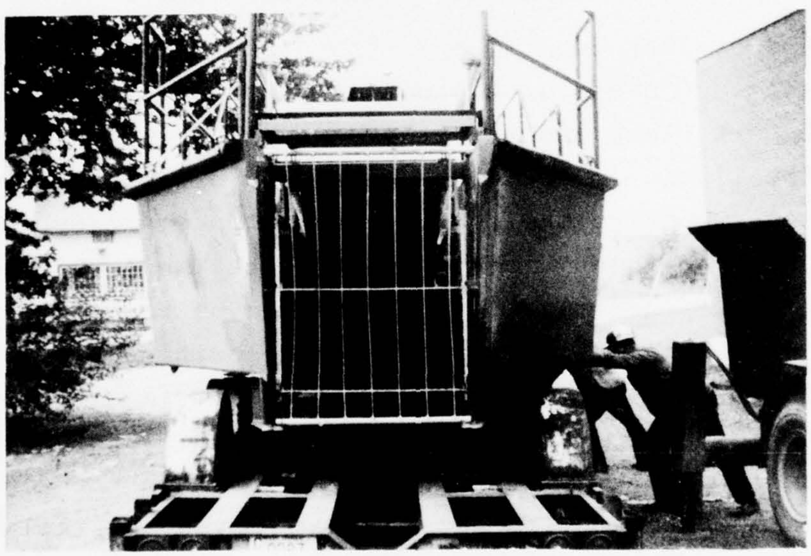


FIGURE 21
TRASH GATE INSTALLED ON THE SKIMMER

battery and a pilot light. This float was mounted approximately 6 inches below the top of the fibers. The rationale behind mounting it at this height was that if the oil thickness was deeper than this, sufficient oil would be present at the weir to ensure high recovery efficiency (for viscous oils, where a deeper oil pool is necessary, lowering of the fibers with respect to the weir would also lower the sensor). This depth was actually deeper than theoretically required for a 100-percent recovery efficiency, and in calm water tests good results were obtained without the sensor indicating sufficient oil. Waves and viscous oils are conditions where the float sensor would not be expected to function as well.

The second sensor type was a capacitance probe, which was expected to give better performance in waves, viscous oils, and emulsions. One probe was mounted approximately 1 inch above the float sensor, and a second one was located near the bottom of the fibers to detect an over-filling condition. This was a breadboard type of unit, and unfortunately, it did not function reliably during the tests. Use of some type of sensor with the prototype is recommended, however.

3.3.9 Mechanical Operation

Areas where mechanical problems with the skimmer components were involved are discussed briefly in this section. In most cases mechanical problems did not affect the oil recovery performance, although several delays were incurred, reducing the number of tests which were performed.

Fiber Box: During raising and lowering of the fibers, the fiber box jammed at certain spots, preventing movement past that point. Only by increasing the hydraulic pressure, torquing one or more of the screws with a wrench, or by hydraulically "shocking" the screws (repeated on-off cycling with main directional control valve) could the box be moved past the jamming point. The precise cause of the jamming was not determined, and several factors may have contributed to the problem.

The main cause of jamming was probably interference between the fiber box and the rather wavy surface of the skimmer hull. After smoothing out some of the hull surface irregularities, operation improved considerably. High friction within the drive train and a limited torque availability from the hydraulic motor may also have contributed to the problem. One simple improvement here would be to modify the method of attaching the box to the Acme nuts, so as not to impose a bending moment on the nut. Replacement of some of the plain bearings with anti-friction bearings would also help to reduce friction.

Belt Mechanism: At one point in testing, the geroter-type hydraulic motor, which drives the belt system, apparently failed. Subsequent teardown revealed the hydraulic motor to be intact but a scored area on the drive shaft indicated that jamming of the main bearing may have occurred under load. To ensure uninterrupted completion of testing, that hydraulic motor was then replaced with a larger motor. Pressure drop data taken later during testing indicated that the original motor would have been sufficient after all.

Two other modifications were made to the system in order to minimize belt drag with viscous oils. First, the steel aircraft cable belt supports were supplemented with aluminum T-sections in order to maintain a 2½-inch clearance between the belt surface and the top layer of fibers. This prevented the belt from dragging on the fibers. However, the 2½-inch clearance proved to be too much in some cases and the T-sections were removed during the final tests. Removal of the T-sections increased the hydraulic pressure requirement,but not excessively.

Secondly, the flat plate slide bed on the return side of the belt was replaced with a conveyor bed of rollers. This helped to eliminate excessive drag between the belt and the return slide, which may occur with viscous oils.

Hydraulics: In general, the hydraulics performed satisfactorily, although the failure of the reusable fittings in the hydraulic hoses was a repeated problem. These hoses were eventually replaced with permanent-fitting hoses, wherever possible. The remote compensator pressure adjustment for the hydraulic pump did not work satisfactorily, so adjustments had to be made at the pump itself, using the screw-adjustable compensator. Minor problems with leaking valves, etc., are easily repairable.

Propulsion: No tests were run using the propulsion system alone (self-propelled oil skimming tests), so any potential problems in this area were not observed. An engine governor that worked better at low rpm would be better for oil transfer operations.

3.4 Performance Testing at OHMSETT

A series of performance tests were conducted at the EPA's OHMSETT test facility during the periods of July 13-24 and August 12-14, 1976. A separate report (being written by OHMSETT personnel) describes details of the test setup and procedures, as well as the complete test results and data. This section briefly describes the test program and summarizes the important points learned from the testing.

3.4.1 Results and Conclusions

The test results in general showed the following:

1. The concept works on a large scale -- parallel oriented fibers are effective in slowing down oil for recovery by conventional means, using operational size hardware.

2. Proper adjustment of a few device parameters is important for optimum performance.

3. Performance in waves was poor, apparently because the tightly strung fibers in this particular model arrangement caused excessive oil-water mixing as the vertical wave components passed through the fibers.

4. Performance falls off rapidly as the design current velocity (8 fps in this model) is exceeded.

5. Use of a solid belt is effective in sweeping the oil to the weir area, but was not particularly effective in reducing the deleterious effects of wave motion.

6. At higher speeds, light oils tend to be more efficiently recovered than viscous oils.

3.4.2 Summary of Test Procedures

The basic test setup is shown in Figure 22. Towing power comes from an endless cable system, to which all three bridges are attached. The oil was distributed from the forward bridge, which was more than 40 feet in front of the skimmer mouth. To ensure that all or most of the oil entered the skimmer in a relatively quiescent manner, parallel guide plates were used. These plates were later replaced with floating ropes for calm water tests, and were removed altogether for wave tests. With waves a wider distribution width was used and the oil encounter percentage was estimated by an observer on the main bridge.

Most tests were recorded on videotape using an underwater television camera. Other tests were recorded on movie film using one of the underwater camera windows along the side of the tank.

Approximately 400 feet of run could be made, giving run times of from 120 to 40 seconds, at tow speeds of 2 to 6 knots, respectively. Nearly all of the tests were run with a 2-millimeter thick slick, resulting in approximately 70 gallons of oil being fed into the 3.5-foot wide skimmer mouth. The corresponding distribution rates ranged from 35 gpm at 2 knots to 105 gpm at 6 gpm.

The general procedure for conducting a typical test is outlined below:

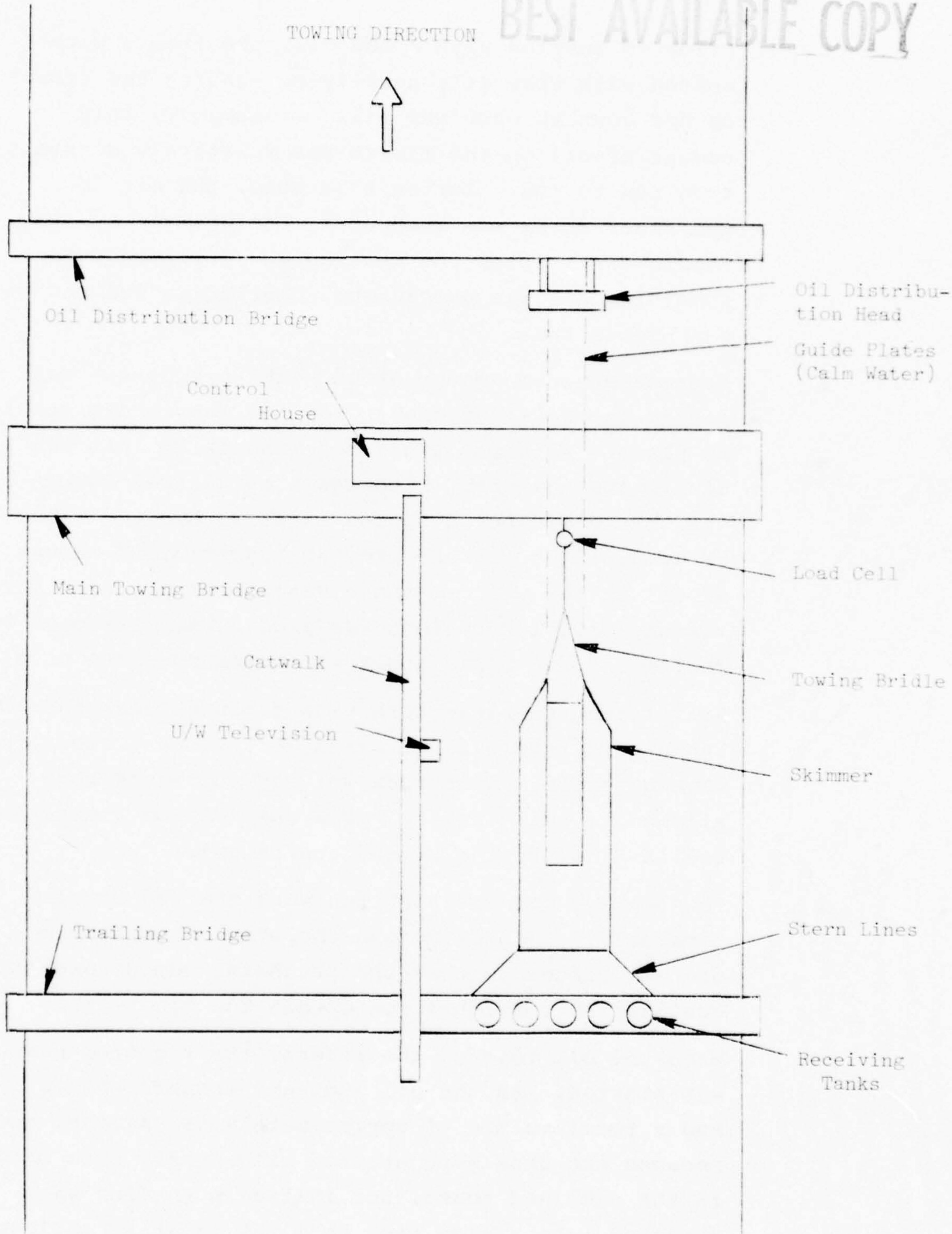


FIGURE 22
EXPERIMENTAL TEST SETUP - OHMSETT

1. Prior to testing with a new oil, the fibers were wetted with that oil, usually by running the fibers up and down through the oil. Presumably, this amount of oil on the fibers was relatively constant from run to run. During this step, the oil in the fiber array was trapped in the skimmer by the fabric dam. After the wetting was performed, the remaining oil was pumped out, simulating the end of a previous run.

2. A predetermined amount of oil (the precharge) was placed in the fiber area, with the fabric dam still in place. With the light oil (Sunvis 7) this was always 100 gallons, which was a calculated amount of oil that could build up and exist within the fiber array during a run and provide a sufficient amount of oil at the weir to avoid water pickup. With more viscous oils 130 gallons was used. Use of a precharge assured rapid achieval of steady-state conditions.

3. All of the run parameters were set,and fresh receiving tanks were readied. If waves were to be tested, the wave generator was turned on, and the waves were allowed to build up (in waves some of the precharge was lost before the actual run began).

4. The tow and oil distribution were started simultaneously. Seconds before the start, the fabric dam was lifted so that the precharge could reach its equilibrium configuration within the fiber array.

5. When the oil reached the fibers, the transfer pump was started. As the oil sump and transfer hoses had a total volume of approximately 65 gallons, and because the runs were started with nearly pure water in the sump and hoses, the initial pump flow was directed into a slop tank until at least 65 gallons had been pumped. The flow was then directed into a steady-state tank for 30 seconds (or more) to determine

a pumping rate and a gross recovery efficiency. At the same time, discrete samples were taken from the discharge line and collected in small bottles at 5-second intervals (sometimes 10 seconds) during the steady-state period. During the steady-state pumping time, the tow had usually stopped, but the oil being sampled was representative of what was recovered during the steady-state portion of the tow.

6. At the end of the tow the fabric dam was replaced and sample taking was continued, as described above. The skimmer was then towed slowly back to the starting point.

7. All of the oil remaining in the system was then pumped into a separate "inventory" container, so that the skimmer was returned to the condition existing at the end of Step 1 above. The amounts of oil in each tank were determined, as well as the relative amounts of oil and water in the steady-state tank and each discrete sample bottle.

Recovery efficiency was defined as the percentage of oil in the steady-state samples. Because of the short run times and the large holdup in the piping, the discrete samples turned out to give a much better indication of the recovery efficiency than the gross sample in the steady state tank. The discrete samples could usually be seen to increase in oil concentration and level off to a steady value, and then (sometimes) fall off near the end of the run. The gross sample nearly always indicated a lower efficiency than the discrete samples.

Throughput efficiency could only be determined on an overall basis and not for steady state. It was determined by the following formula:

$$\frac{\text{Total oil recovered in slop, steady-state, and inventory tanks-Precharge}}{\text{Total oil distributed} \times \text{fraction of oil encountered by the skimmer}} \times 100\%$$

$= \text{Throughput efficiency}$

A subjective feeling for throughput efficiency was also obtained from visual observations of oil losses, either directly (above water) or from the underwater video.

The test condition parameters are listed below. Not all combinations of parameters were tested, however.

Oil Type	30 cs (Sunvis 7), 143 cs (lube mix), 760 cs (Sunvis 1650) (nominal viscosities-varied during tests)
Tow Speed	2, 4, 5, 6 knots
Thickness	2mm, 4mm
Distribution Rate	35, 70, 88, 105 gpm (based on 100% encounter)
Distribution Width	3.5 feet (with guide plates or ropes) to 7 feet (free distribution)
Waves	A. 2-foot harbor chop
	B. 15.2" height, 17' length, 1.9 sec. period
	C. 16.5" height, 35' length, 2.7 sec. period
Seas	Head and following

The device parameters are listed below. Again, not all combinations were tested.

Fiber depth	Top fibers exposed, top fibers submerged (actual depths varied with conditions)
Trim	0° to 2.9° (all bow up in the at-rest condition)
Weir Depth	2 to 4 inches (target settings -- varied with runs)
Belt Speed	0 to 3 fps

3.4.3 Discussion of Results

The detailed data from each of the fifty runs completed is contained in a report being prepared by OHMSETT personnel. This present section will cover the significant findings and discuss their implications on the next stage of development.

Because of the large number of parameters to be investigated, the test strategy was to optimize overall performance by separately adjusting individual device parameters. However, with the relatively few tests conducted, the testing could produce only general indications of which adjustments were good and which were not. Several parameters interacted with each other, such as the combination of fiber depth, vessel trim, and weir depth, and also the fiber depth and belt position, making optimization difficult.

With the limited number of tests available, optimization was studied mainly at 4 knots (light and heavy oils). Parameter settings for heavy (viscous) oils (Sunvis 1650 or lube mix) at speeds other than 4 knots were generally set based on light oil (Sunvis 7) performance, but occasionally these settings were not right and one or more of the performance parameters suffered. This accounts for some of the irregularity in the data, particularly in the area of recovery efficiency. Scatter in the throughput efficiency data could be attributed partly to changes in the measurement procedures, which were evolving throughout most of the test period, and partly to the large holdup in the system, which required taking the differences in large numbers to calculate oil losses.

Although all of the terms in the throughput efficiency definition were subject to measurement error, measurement of the difference in holdup volumes in the skimmer before (precharge) and after (inventory tank) was the most likely to be in error, and would have the biggest effect on the efficiency calculation.

Theoretically, at steady-state, the difference in these two relatively large volumes would be zero; a difference would indicate oil losses and/or unequal encounter and recovery rates. In the test setup, however, a difference could also be caused by a change in the amount of "equilibrium" oil clinging to the fibers (probably most important with the Sunvis 1650) or by oil leaking to or from the space between the movable fiber box and the surrounding hull (most important with Sunvis 7, which could leak faster due to its low viscosity). In the latter case, any oil contained in this area was assumed to stay constant, but when long time periods elapsed between operations,oil had time to equilibrate over the entire surface; the effect would be to show a higher than actual efficiency if oil leaked from the side/back area into the fiber area and was included in the final inventory, or a lower than actual efficiency if oil leaked the other way and was not included in the final inventory. This particular source of error was finally eliminated (during the Sunvis 1650 runs) by raising the fiber array clear of the water before pumping out the oil into the inventory tank at the end of a run. Difficulties in raising the fiber box during the Sunvis 7 tests prevented taking this approach earlier.

The space along the back and side of the fiber box was approximately 18 percent of the fiber area. For a typical run involving 65 gallons of distributed oil and 100 gallons of precharge, the error caused by leakage to or from the back and sides could amount to 20-30 percent in the throughput efficiency. Coupled with errors of 5-10 percent in the other factors, as much as 50-60 percent overall error was possible, although the probability of general random errors occurring simultaneously in the worst combination was remote.

The errors in general appeared to be much less than indicated above. For Sunvis 7 at 4 knots in calm water there

were nine similar runs in which parameters were somewhat close to optimum; the mean throughput efficiency was 93.0 percent,and the standard deviation was 9.3 percent (See Figure 23). Assuming that the deviations from the mean were caused only by a normal distribution of random errors (which they were not, because parameters were being varied, also) the 95-percent confidence limits on the mean were $\pm$ 7.0 percent; or stated differently, 95 percent of the time a series of nine similar runs would be expected to have a mean throughput efficiency of between 86 and 100 percent. For the same oil, the confidence limits on the mean at other tow speeds would be expected to be similar. However, runs at other speeds usually produced only one or two valid runs (somewhat optimized) and this inference could not be checked. The single 2-knot runs appear, therefore, to be extraneous data points, because the actual throughput efficiency appeared to be nearly 100 percent, based on video observations. In the case of the 2-knot Sunvis 7 run, a flow of oil from the back and sides into the fiber area probably contributed heavily to the high efficiency value. The 2-knot Sunvis 1650 run was hampered by high winds blowing the dispensed oil out of the path of the skimmer,and the skimmer encountered mainly the thicker, center portion of the slick (spreading of this viscous oil was slow), thereby encountering and recovering more oil than assumed in the throughput efficiency calculation.

In reality, most of the value from the test program came from the subjective observations of actual performance made by the project personnel. The relatively few data points did not always support these observations (e.g., the 2-knot runs, discussed above), and because of the number of parameters involved, statistical manipulations of the data to determine trends could not be justified either.

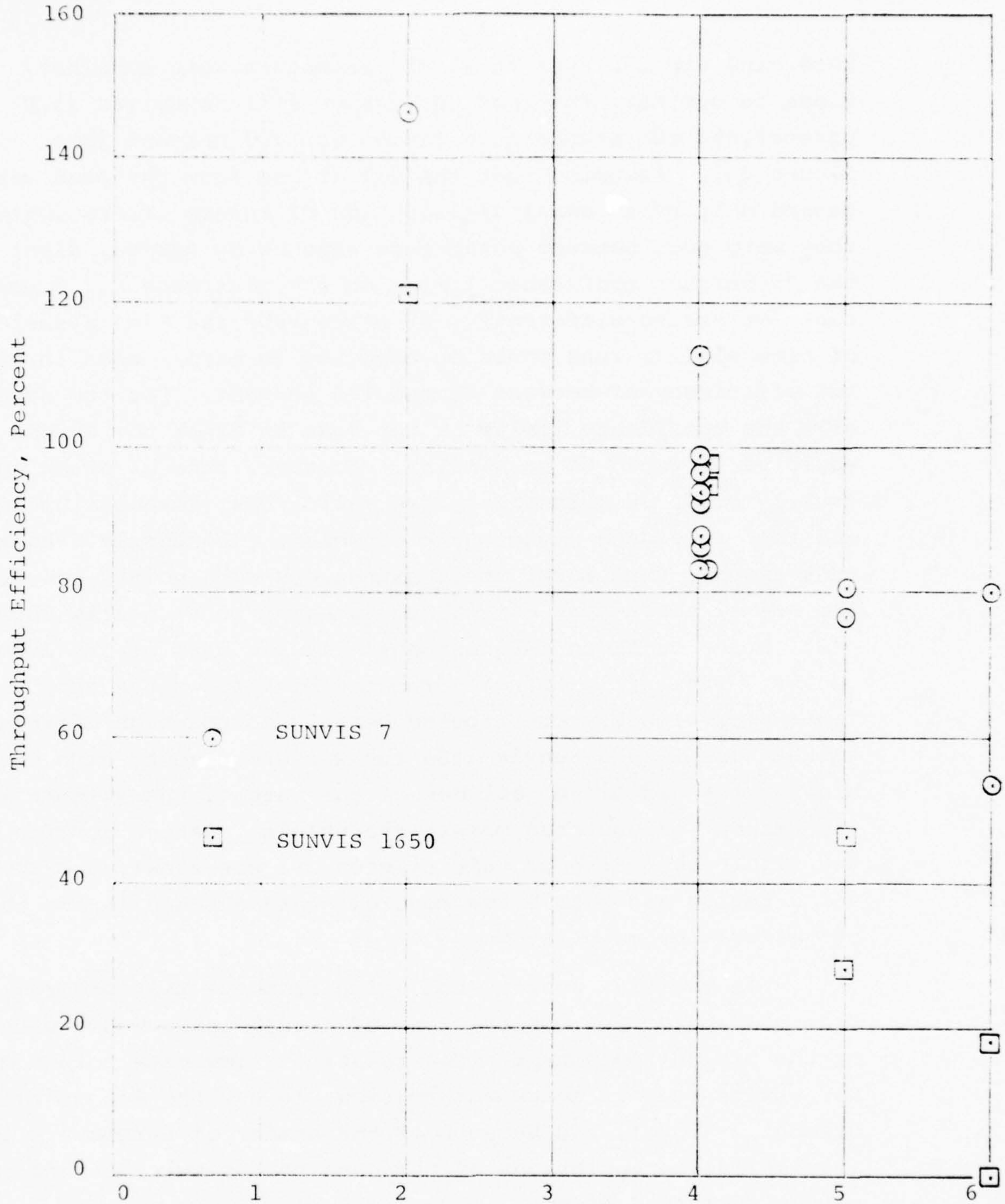


FIGURE 23 THROUGHPUT EFFICIENCY, CALM WATER

In general, it was found that proper setting of the device parameters was very important for successful operation, but only up to a point; eventually, certain basic limitations of the system became controlling. The discussion to follow points out what the limitations appear to be and what changes could be made to improve performance. The problems were somewhat different between calm water and wave conditions, and these two conditions will be discussed separately.

Calm Water Tests: The device was designed primarily to operate efficiently in calm waters, such as in rivers, where natural high currents exist and where low-speed skimming techniques are not practical (for example, drifting with the current so that the current speed relative to the skimming device is low). Based on the assumption that internal head-wave entrainment losses would limit the practical application of the concept to around 5 knots (see Section 3.2), a design speed of 8 fps was used to determine the fiber length. Indeed, the throughput efficiency of the device with a light oil (Sunvis 7) and somewhat optimized device parameters showed good performance up to this speed. Figure 23 shows the experimental results supporting this observation. Recovery efficiency was also excellent, as seen from the data in Figure 24. The recovery efficiency values are from the discrete samples taken during the run.

To achieve these results with light oil, it was important to have the top fibers above the surface at all points in the device, as shown in Figure 25. When the fibers were lowered so that a jet of unrestricted water came over the top, losses were heavy. This was mainly because the top jet of water and light oil did not have its kinetic energy dissipated, and flowed down through the fibers and out the bottom near the end of the device at high velocity. This phenomenon could be seen on the video as a heavy loss with a sharp downward direction to it.

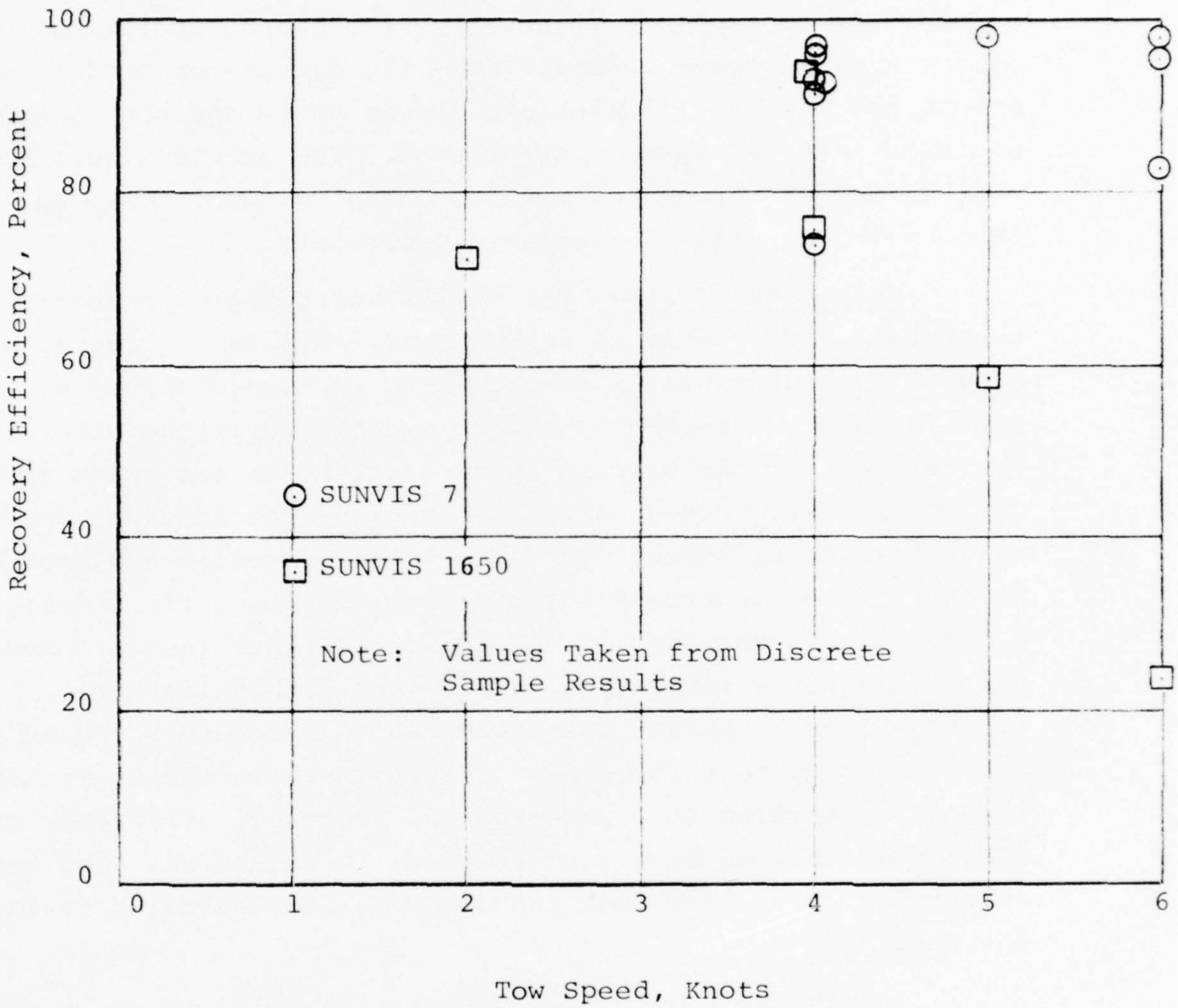


FIGURE 24 RECOVERY EFFICIENCY, CALM WATER

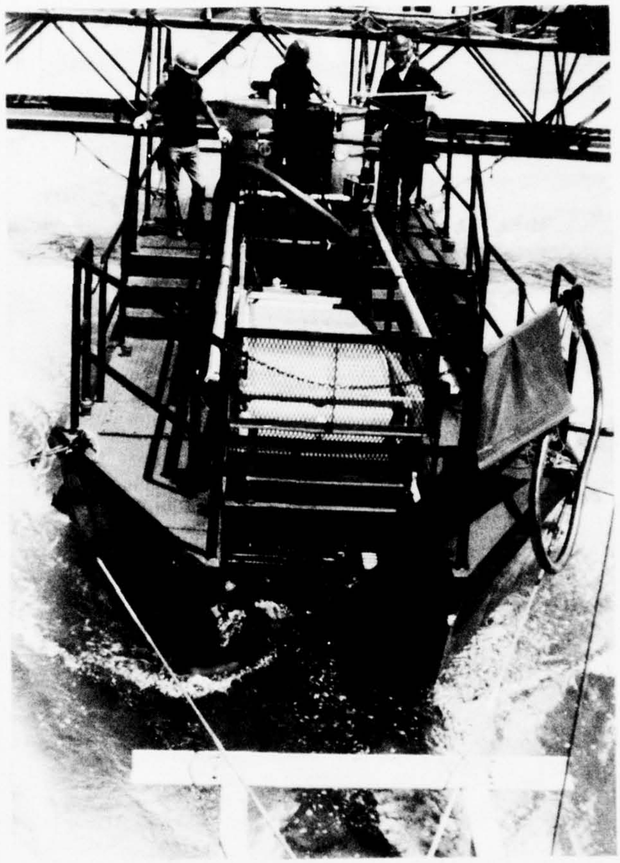


FIGURE 25
TYPICAL CALM WATER TEST WITH LIGHT OIL

With the fibers above the surface, the light oil flowed easily to the weir where it accumulated in a pool deep enough to be skimmed off at high recovery efficiency, typically 95-98 percent. The belt was not needed in this case.

With viscous oil the system had to be operated differently to achieve good results. To provide sufficient oil at the weir for good recovery efficiency, the moving belt had to be kept in contact with the oil surface. To do this, the top fibers had to be lowered into the water, creating a similar situation to the one that caused oil losses with the light oil. In this case the jetting problem was not as severe as before because as the viscous oil accumulated and adhered to the fibers, the water jet was forced into the fiber array further forward; therefore, it had time to dissipate some of its energy. As not all of the jet energy could be dissipated, losses were somewhat greater than with the light oil. Figure 23 & 24 shows how efficiency for the 700-CS (SUN 1650) varied with run speed.

In heavy oil runs where the top fibers were kept above the surface, the losses (video observations) appeared to be less than those from light oil runs at the same speed. In this case, the high viscosity appears to have helped to stabilize the oil in the fiber matrix, although this same stabilizing prevents the oil from flowing readily to the weir area. A substantial buildup was no doubt occurring within the fiber array, however.

Weir performance was more critical with the viscous oils, partly because of densimetric Froude number effects. Studies by Beach, et al[6], showed that the critical densimetric Froude number, Fr_c, at which no water would be collected over an oil-separating weir varied with viscosity. Values ranged from a low of $Fr_c = 0.3$ for a 2100-cs oil to $Fr_c = 1.0$ for a 4-cs oil. A correlation of Fr_c versus oil viscosity was not determined, however, The densimetric Froude number is defined as follows:

$$Fr = \frac{U}{\sqrt{(\Delta h \, g \, \frac{\Delta\rho}{\bar{\rho}})}} \qquad (5)$$

where: U = average velocity over the weir

Δh = height between the oil-water interface and the weir lip

g = gravitational constant

$\Delta\rho$ = difference in density between oil and water

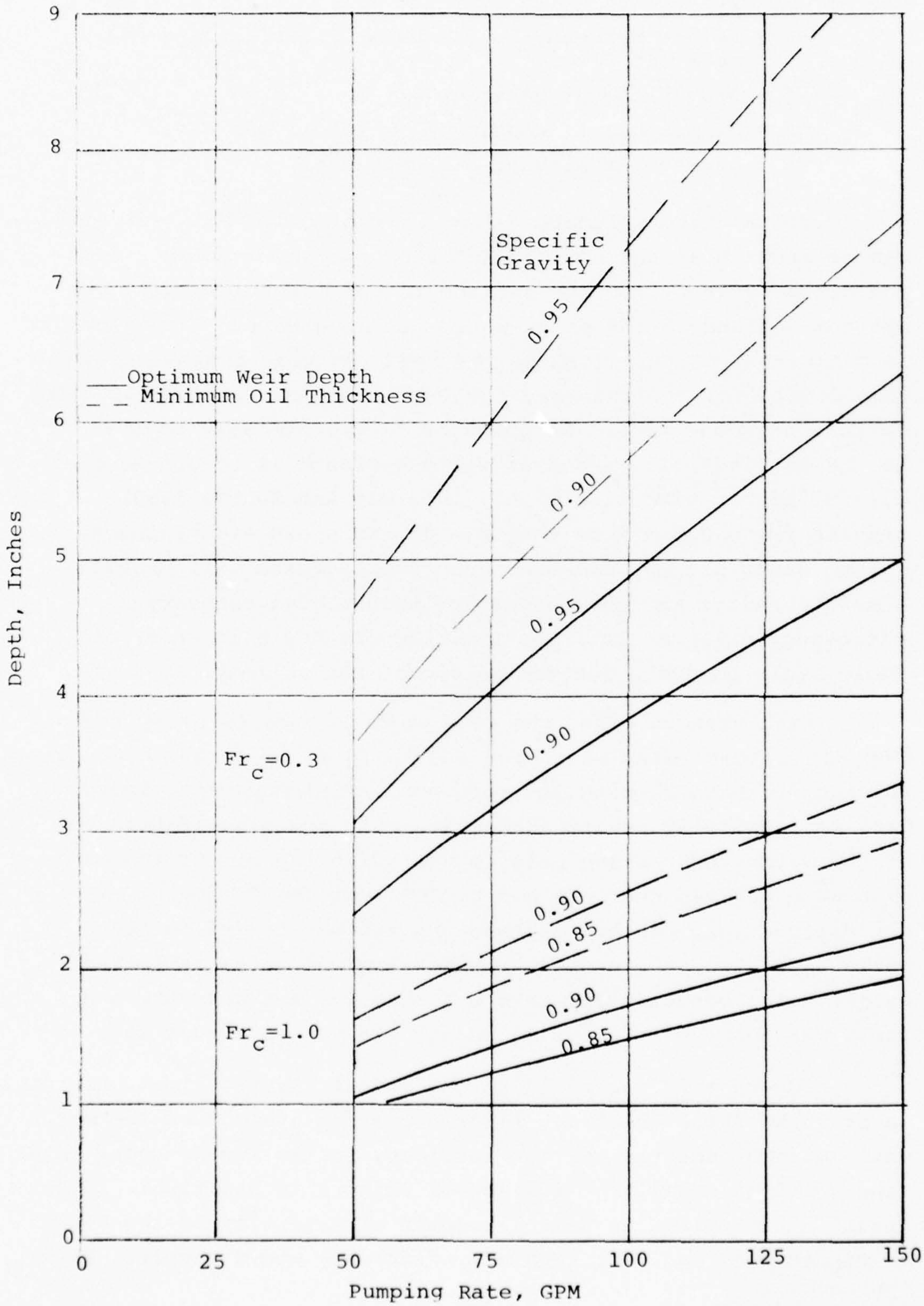
$\bar{\rho}$ = average density of oil and water

For a given volumetric flow rate of oil over a weir it can be shown that the optimum location for the weir is 2/3 of the distance down from the surface to the interface, with the optimum defined as the point where the densimetric Froude number is minimized. Figure 26 shows the required weir depths and interface depths for the skimmer, for Fr_c values of 0.3 and 1.0, and various oil densities. Although $Fr_c = 1.0$ probably applies to the Sunvis 7 oil, a conservative approach is to assume that oils of higher viscosity (i.e., lube mix and Sunvis 1650) require $Fr_c = 0.3$. Note that the depths shown are minimums for no water pickup, and that deeper oil depths will provide a safety factor and more assurance that a high recovery efficiency will result. The limiting oil depth is where oil would begin to drain out the bottom of the skimmer.

With viscous oils, the belt must be used to sweep the oil over the fibers to the weir area and build it up to the necessary thickness. Data showing low recovery efficiency with viscous oils was generally due to inadequate belt sweeping (fibers out of the water, preventing belt contact with the oil, or too much clearance between the belt and fibers with the T-bars in place), or improper weir depth. Because the skimmer tended to squat while under tow, the proper weir setting had to be estimated before hand; occasionally this estimate was not correct, and there was not sufficient time during the run to adjust it.

Bow-up trim was added to the vessel for the light oil runs, in order to raise the front fiber support plate out of the water while maintaining the weir at least one to two inches under water (the weir was usually at its lowest adjustable position). With insufficient trim, the weir lip would occasionally be too close to the surface and poor recovery efficiency would result. This

FIGURE 26 . WEIR CHARACTERISTICS FOR LARGE-SCALE MODEL VS PUMPING RATE



problem could be easily corrected by modifying the box to increase the adjustment range of the weir. Keeping the front plate out of the water surface did help to minimize surface mixing; the resistance of the fiber support bars caused a rise in the water surface at the entrance to the fibers, and the trim kept the plate above the surface.

The oil recovery rate was, of course, a direct function of the pumping rate and recovery efficiency. With the enlarged clearances in the pump (for more efficient pumping of viscous oil) and the available hydraulic flow control valve, only about 130 gpm of fluid could be pumped. However, this was more than enough to handle most of the test conditions. In nearly every test the pump rate was set ahead of time for the anticipated flow, assuming all oil would be recovered. Oil recovery rates could have been increased in several cases by merely increasing the pumping rate.

At four knots in light oil tests, small clouds of oil bubbles could be seen coming from the bottom of the device. With viscous oils any losses appeared as relatively few larger bubbles. This difference could possibly be attributed to the low interfacial tension caused by adding a surfactant to the oil. IFT values for the light oil were reported in the range of 5.6 to 14.5 dynes per centimeter.

Wave Tests: Performance in waves was dramatically different than in calm water. In no test did throughput efficiency exceed 45 percent, and many tests had negative throughput efficiencies, indicating loss of the precharge during the run. The following general trends were observed:

1. Throughput efficiency appeared somewhat better in the two-foot harbor chop than in the regular waves (with head seas).
2. Throughput efficiency in following seas was better than in head seas (regular waves).
3. Throughput efficiency at two knots was better than at higher speeds (all two-knot runs in harbor chop had positive efficiencies.)

4. Throughput efficiency with light oil appeared to be better than with heavy oil.

5. Recovery efficiency in following seas was significantly better than in head seas (regular waves).

6. Recovery efficiency with light oil was better than with heavy oil.

7. The belt was no help in increasing recovery efficiency in head seas or harbor chop (viscous oil).

8. Recovery efficiency in harbor chop appeared to be better than in regular waves (head seas, low viscosity oil).

The basic reason for the lack of good performance in waves appeared to be stiffness of the fibers and fiber box; i.e., the fiber and weir do not conform to the wave profile. The relatively short steep regular waves produced in the tank cause extreme surface variations within the fiber array. A typical tank wave, 15.2 inches high, 17 feet long with a 1.9 second period, will produce a surface variation of nearly 3/4 of the fiber bed height, with no chance of the vessel following the wave because of the short wave length. This surface movement permits the oil located near the surface to approach the bottom of the array, where it can drain out the bottom. Also, with a typical skimmer velocity of four knots in head seas, this movement occurs at an encounter period of approximately one second, causing excessive mixing as the fluid flows perpendicular to the fibers.

Another reason for loss was probably because some of the wave crests passed over the fibers where the flow energy could not be dissipated. The belt helped force some of the crests into the fibers, but crests passing along the sides of the belt (the belt width was less than the fiber box width) did not stop until they broke at the weir. Even with the wave crests forced into the fibers, the orbital wave velocities, when superimposed on the towing velocity, would increase the instantaneous velocity, thereby increasing the theoretical fiber length requirement for complete slowing. Therefore, the device may have lost some oil as though the fibers were too short, and possibly longer fibers would have been helpful at the higher speeds.

In following seas the oil-water interface must still traverse the same fiber height, but the encounter period can be much longer depending on the relative wave and vessel velocities. This will reduce considerably the degree of mixing intensity, and will reduce the wave action at the weir, improving recovery efficiency. Both of these effects were seen in a comparison of 4-knot runs in head and following seas.

The harbor chop waves did not have the periodicity to them that the regular waves had, and the motions within the fiber array were therefore less. Vessel motions were also less pronounced than in the regular waves, which tended to cause rather large pitching motions at the wave lengths tested. Lowering the skimming speed probably improved throughput efficiency by causing longer period motions, and therefore less mixing.

Wave-induced motions at the weir caused the interface to oscillate up and down and permit water flow over the weir. This is directly related to densimetric Froude number effects, which were discussed previously, and the only solution would be to maintain a larger thickness of oil in front of the weir. However, with heavy losses and mixing taking place, the oil actually thinned out, even with the belt in operation. There was some improvement in recovery efficiency in harbor chop, probably because of the less severe mixing and interface movement at the weir.

The apparent improvement in light oil performance over heavy oil performance may also have been because of densimetric Froude number effects. With the high degree of mixing going on, the oil was present as small droplets dispersed in the water phase; the increased buoyancy of the light oil droplets may have helped prevent them from being drawn out the bottom.

The above results indicate that if the device is to operate effectively in short steep waves, much better wave

conformance must be built into the fibers. Although a fiber tensioning feature was available on the fiber box, this was mainly for installation purposes, and adjustments could not be easily made. The most effective method of improving wave conformance would involve floating the front and rear fiber support assemblies, as well as the oil collection sump and weir. A design for accomplishing this is given in Section 4.2.2.

3.5 Development Testing

To aid in design of the large-scale model and the prototype, two separate laboratory test programs were undertaken. The first was a series of exploratory oil recovery tests conducted in the Coast Guard flume, located at Seaward's Clearbrook facility. The second was a program in the towing tank at the Stevens Institute Davidson Laboratory, where resistance and motion studies were made for the proposed hull shape. These two programs are described in the following sections.

3.5.1 Small-Scale Model Testing

Description of the Test Facility: Prior to development of a large-scale model design, extensive small-scale model testing was performed in a recirculating flume provided by the Coast Guard. An overall layout drawing of the test facility is shown as Figure 27. By removing the original honeycomb flow straightener at the entrance region of the test section, nominal water velocities of up to eight feet per second could be achieved.

Four steel oil storage tanks, each with a capacity of 1000 gallons, contained the oil to be distributed, and the oil-water mixture recovered.

Oil was dispensed immediately in front of the fiber array model, through a calibrated positive displacement pump, and jetting-type dispenser nozzle. Oil recovered by the model was pumped through an identical gear pump and into the storage tanks. Efficiencies could be measured from small discrete samples taken at the pump discharge or from bulk volumes of oil delivered and recovered. Any oil lost by the device was eventually recovered in the calming section of the flume, using a SLURP floating weir-type oil skimmer.

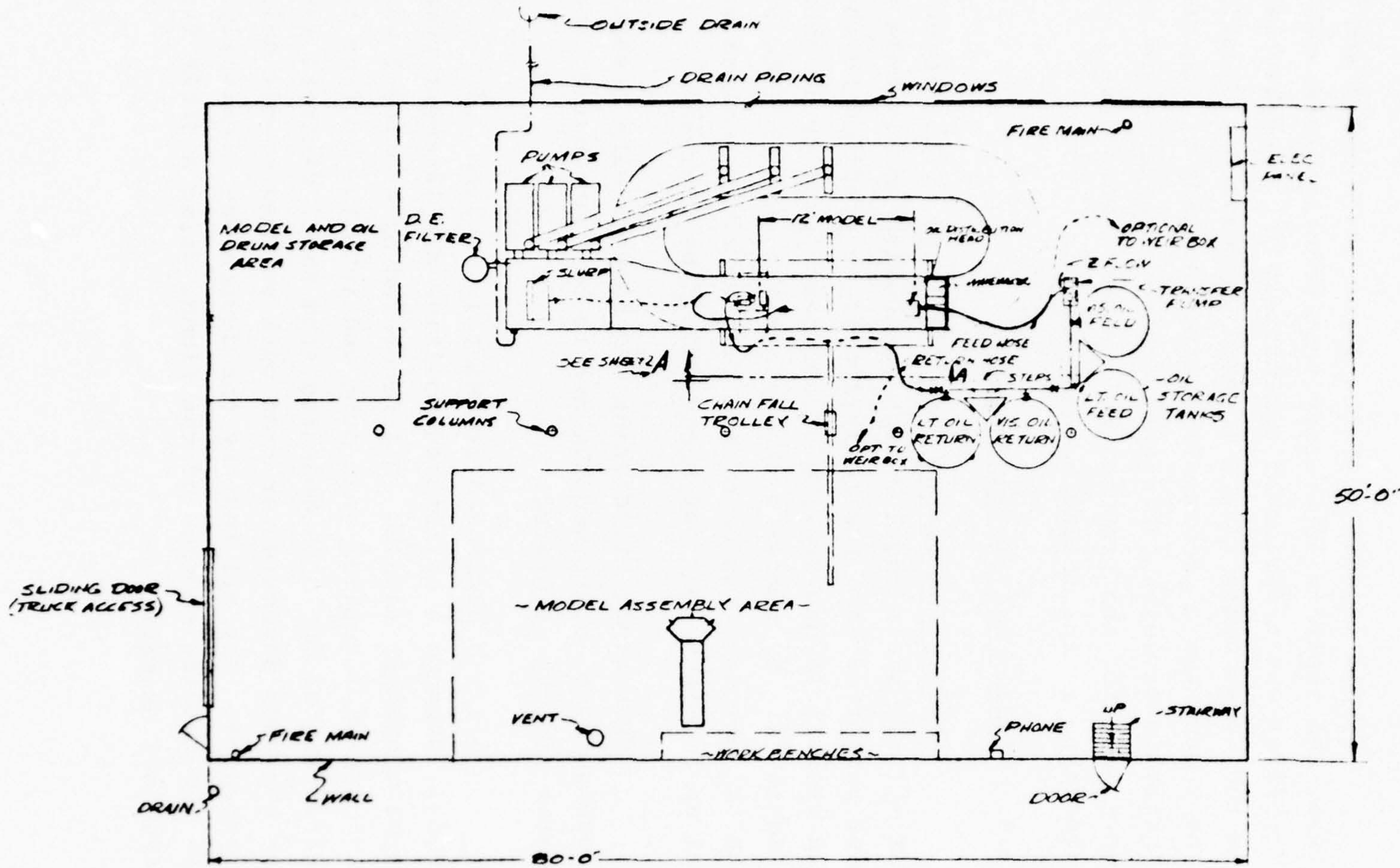


FIGURE 27. OVERALL LAYOUT OF THE CLEARBROOK TEST FACILITY

Basic Procedure of Model Testing: Although the specific procedure of flow tank testing varied somewhat depending on the parameters being investigated and the devices being tested, testing usually followed a common basic procedure. This procedure was as follows:

1. The flume current velocity, wave conditions, oil delivery and recovery rates, skimmer model draft, and other operational parameters were set at the desired values.

2. The oil delivery pump was then started and the oil level inside the test model was observed as the oil entered the device. The oil recovery pump was turned on after a certain amount of oil build-up, and the flow rate adjusted where necessary to prevent excessive thickening.

3. During each test, which typically ran 5 to 15 minutes, the secondary oil pickup system was adjusted as necessary and the oil level within the device was observed and recorded at various points with a hand-held, triangular, plexiglass, viewing device. This was made necessary by the turbidity of the water after several minutes of testing.

4. During the tests, small samples were periodically taken from the discharge port of the recovery pump. These samples were later analyzed by volume to determine oil-water recovery ratios.

5. At the end of the test, the oil delivery pump was shut off and the recovery pump allowed to run until the remaining oil inventory within the device had been recovered.

6. Throughput efficiencies for each test were then computed from oil and water level measurements taken after each test, from the delivery and recovery storage tanks.

Parameters measured where applicable during testing included:

- Water velocity
- Water temperature
- Wave conditions: wave length, wave height
- Type of oil used
- Oil temperature
- Oil viscosity: before test, after test
- Specific gravity of oil: before test, after test
- Oil delivery rate
- Oil pick-up rate
- Pick-up subsystem used
- Operating values for subsystem: belt speed, geometry, location, etc.
- Oil levels within the device during operation
- Time of test
- Time of samples
- Apparent oil-water ratio of samples
- Oil-water ratio of "apparent oil in samples" after centrifuging
- Qualitative observations

Three different types of oil were used for testing: No. 2 fuel oil (viscosity 5 cp at 16°C), Gulf Security 53 (viscosity 240 cp at 16°C), and Exxon Coray 65 (viscosity 1000 cp at 16°C). The specific gravities ranged from 0.85 to 0.92.

Summary of Flume Testing Sequence Results: The fiber array model, consisting of a three-sided enclosure, with an array of parallel streaming polypropylene monofilament fibers, is basically similar to the final model previously tested at the University of Michigan, and is fully described in the Stage I final report[1]. Modifications to the device include the addition of a weir and sump collection area at the rear of the device, which was piped into the recovery pump, and a modified array of fiber supports used to cut down the blockage of flow at the front of the device.

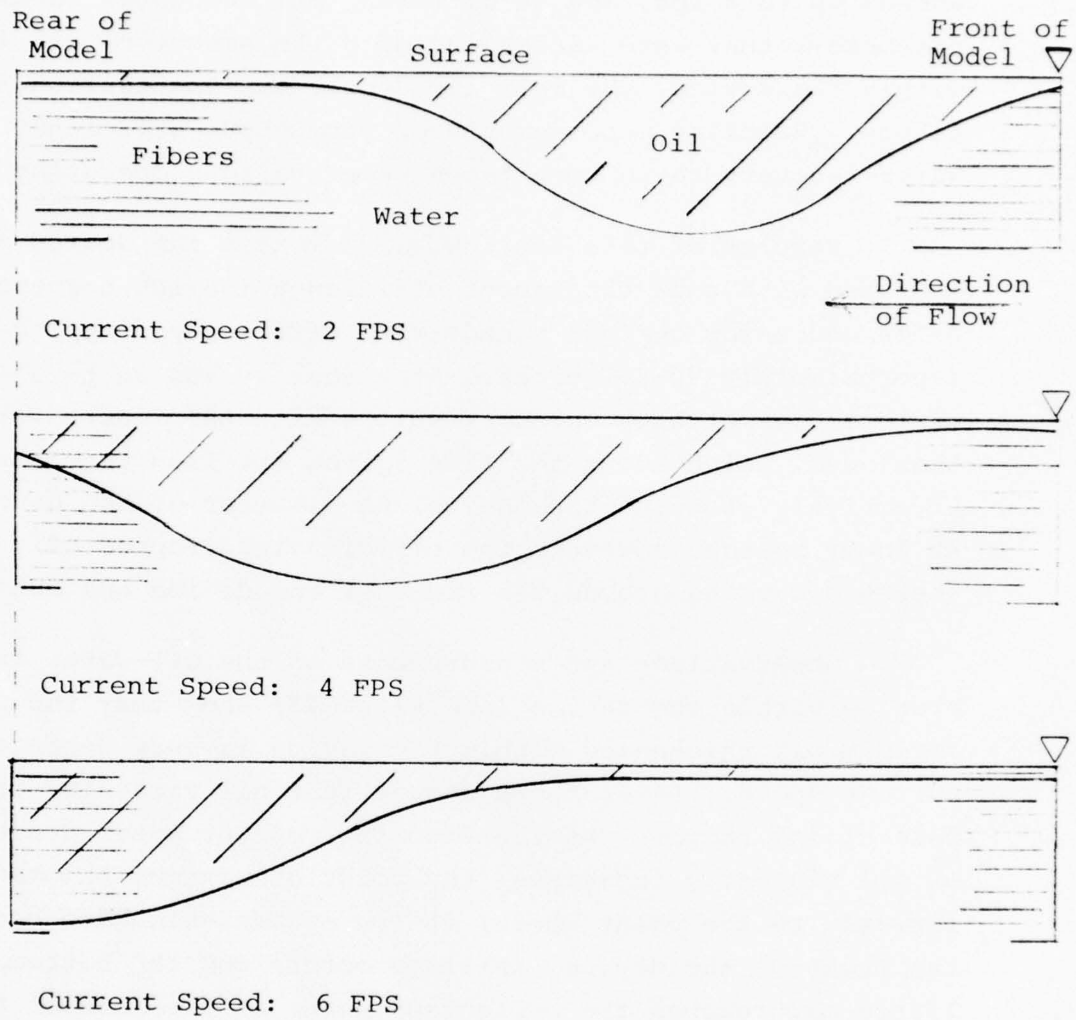
In a first attempt to determine the importance of different operational variables upon the performance of the basic fiber array system, a series of baseline tests were run using the unmodified fiber array model, and using only the weir sump in the back of the device for oil collection. These tests were all run with the model at 12-inches draft such that the top layer of fibers was at the surface. Tests were run at various current

speeds up to 8 fps, and at different oil encounter rates. Other parameters that were varied included the amount of oil inventory within the device, the weir lip depth, and the tension in the fibers. Baseline measurements of throughput efficiency and oil-water recovery ratio were taken under various operating conditions.

Results of this testing indicate that the device could be operated with good throughput efficiency (90-100 percent) between 3-fps and 6-fps current speeds with efficiency dropping off somewhat (approximately 70-80 percent) at higher speeds up to 9 fps. Best efficiencies at high speeds resulted with the fibers very tightly tensioned, which keeps the fibers from sticking together and effectively changing the equivalent diameter of the device. At lower speeds, however, the efficiencies dropped off, with losses occurring around the front of the device and out the bottom.

Observations and measurements of the oil-water interface profile within the device (see Figure 28) show that the point of maximum oil thickening within the device is very dependent on the current speed. Later tests showed that oil viscosity is also a determining factor. As the incoming current speed decreases, or as oil viscosity increases, the point of maximum thickening moves forward, to the point where, at low speeds, blockage occurs at the front of the device, spillage occurs out the bottom, and very little oil reaches the collection point at the rear of the device. While some losses occurred due to oil bubble entrainment at the highest speeds tested, the catastrophic failures at low speeds were the greatest problem with the device.

In a first attempt at solving this problem of low speed failure, a series of tests were run to study the effects of changing the draft of the device such that the top layer of fibers were submerged by various amounts. It was felt that at low speeds the fibers could be completely submerged by several inches, and that the kinetic energy of this unrestricted layer of incoming oil would effectively serve to move the oil layer



Note: The interface levels shown are typical of those resulting with fibers at the surface and no secondary oil transport mechanism used. Length and depth are not to same scale.

FIGURE 28. OIL-WATER INTERFACE PROFILES

towards the rear of the device where it could be collected at the weir.

Results of this testing show that, while this method of oil transport did work efficiently under certain carefully controlled conditions of current speed, pumping rate, and model draft, these operating parameters were very critical. If the momentary draft of the device changed even a small amount, or if the current speed temporarily increased or decreased, or if the oil inventory within the device changed, the oil transport and recovery would be drastically effected. It was concluded that this mechanism of oil transport alone would be impractical and ineffective for use in the field. Some sort of oil transport or pick-up device was needed to supplement low speed operation.

Tested in conjunction with the fiber array were several experimental models for secondary oil transport and pick up. All the concepts considered and tested fit into three basic categories: those that pick up oil directly at the point of thickening, wherever that occurs; those that somehow control the point of thickening such that it always occurs at the weir lip in the rear of the device; and those that pick up and/or transport oil from the natural thickening area to the rear of the device, where it is recovered at the weir sump.

The first device tested fits into the first category. This was a movable skimmer head, very similar to that described in the Stage I final report, and was to be used as an alternative to pick up at the weir. The model varied from that used in Stage I basically in that it had a wider collection area. This device attached to the suction hose of the recovery pump and was manually located such that the oil could be picked up directly at or near the surface in the region of maximum oil thickening. However, testing in various positions and under different conditions proved the device to be ineffective.

Wherever the device was placed in the fiber array, the point of thickening would move either forward or aft of the pick-up point, or oil would stream past the head and spillage would occur out the rear of the fiber array.

Several attempts at controlling the point of oil thickening, so that it would always occur at the weir lip collection point, were also tested at low speed. By lowering the fibers significantly below the surface (i.e. 6-inches submergence) and placing an inclined plane or rotating drum at a controlled point in the surface water flow, it was thought that the point of incoming oil contact with the fibers could be controlled. By controlling this point of fiber contact, the effective fiber length, and thus the point of maximum thickening, could be adjusted so that thickening would naturally occur at the weir lip.

Although this concept did prove effective at low speeds, at higher speeds the jetting effect of these devices resulted in oil bubble formation and entrainment losses. Tests were run in the same manner using the moveable skimmer head and inclined plane devices together, with similar results.

Another pick-up system tested was a rotating sorbent belt system shown in Figure 29 and Figure 30. This device was designed such that the sorbent belt contacts the surface of the slick toward the front of the device, and sweeps toward the rear of the device.

The belt could be driven at any speed up to 10 fps. The sorbent belt worked in two ways to recover oil. First, by acting on the surface of the slick, it could sweep oil towards the weir sump collection area. Secondly, the oil absorbed by the belt was squeezed out between two pinch rollers (See Figure 29) where it would pour into the collection sump. By employing both methods

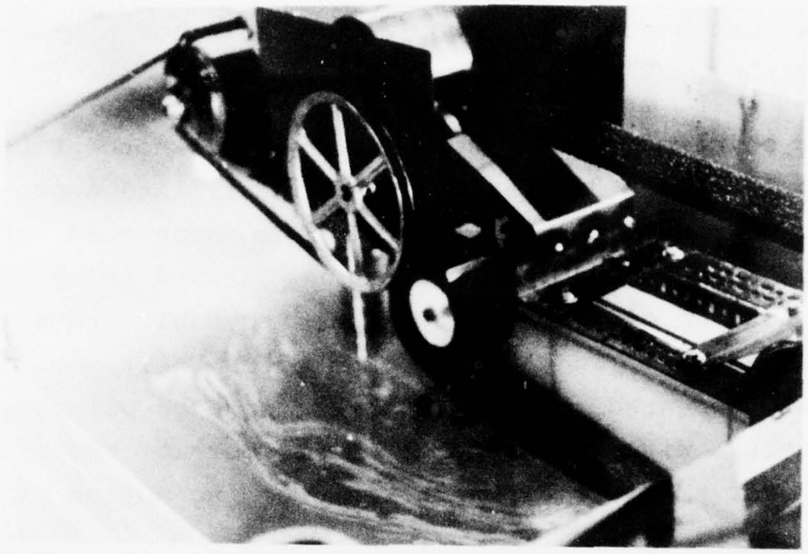


FIGURE 29. SMALL-SCALE SORBENT BELT SYSTEM - DRIVE AND PINCH ROLLERS

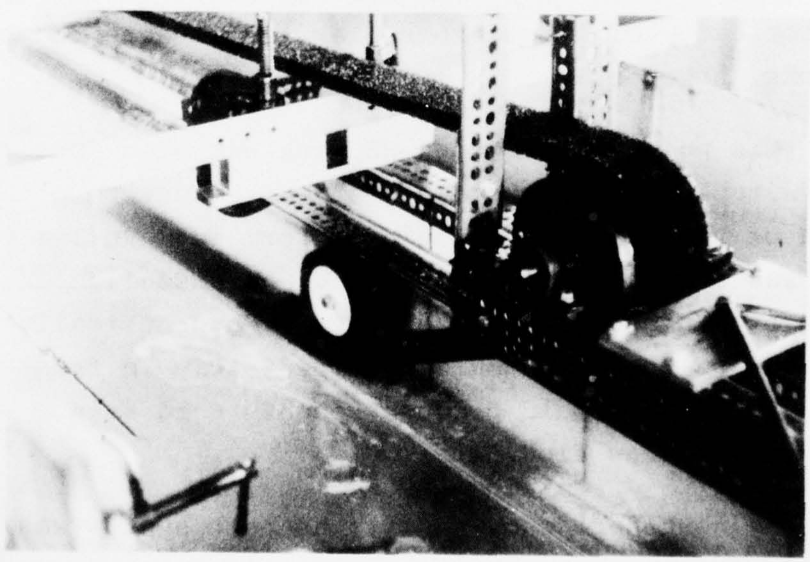


FIGURE 30. SMALL-SCALE SORBENT BELT SYSTEM - FORWARD TENSIONING ROLLER

of pick-up, one sorbent belt would be usable for a wide range of oil viscosities.

For comparative purposes, two types of sorbent belts were tested: a 1/2-inch thick belt of Astroturf, and a one-inch thick belt of Scott 10-ppi reticulated urethane foam. Constant tension on the belt was provided by the forward idler roller, which was mounted on a spring-tensioned moveable frame assembly, shown in Figure 30. In the case of the foam belt, most of the oil recovery appeared to be through drainage of oil squeezed from the belt. With the Astroturf belt, more of the oil was recovered over the weir lip with the sweeping action of the belt.

In either case the system performed with excellent throughput efficiencies (90-100 percent) over a range of speeds from 1 fps to 6 fps, and good efficiency (approximately 80 percent) up to 9 fps. The fluid recovered was almost pure oil with both belts. The optimum belt speed proved to be in the range of 2 to 3 fps, resulting in a maximum thickening point near the rear of the device, even at extremely low current speeds. Belt durability and the complexity of a squeeze roller system were thought to be drawbacks, however.

At this point in testing, no work had been done in waves, as the flow tank had no wavemaker. In an effort to get some indication of how the system would perform in waves, a crude wavemaker was built from parts on hand and installed in the flume. Consisting of a hinged oscillating vane, hydraulically driven, and operating on the water surface immediately in front of the model, the wavemaker could produce roughly 6 to 8-inch waves while the current was flowing.

In the next series of tests, the belt system was used with the wave maker in operation, producing 7-inch waves. The system continued to perform well at low speeds, but at higher

speeds, the incoming waves would break against the forward inclined portion of the belt, which was under tension and positioned inflexibly with a fixed guide roller, as shown in Figure 31. This resulted in oil-water mixing and considerable oil losses. The belt system had proven its ability to transport and recover oil effectively, but lacked the flexibility to conform to incoming waves. The belt system was, therefore, modified extensively such that the belt was untensioned and free to conform to incoming wave crests. The belt operated with no forward guide roller as shown in Figure 32 and lay slack on the surface of the incoming oil. The drive and pinch rollers were at the front of the device with only a set of guide rollers at the rear.

Although the sorbent belts had performed well in previous tests, it was decided to test a smooth-surfaced, neoprene, conveyor belt. This would result in a longer belt-operating life and eliminate the need for sorbent squeeze rollers. This type of belt system transports oil only by a sweeping action to the rear of the device, where it is picked up at the weir sump as shown in Figure 33. A scraper blade was used to free clinging oil from the surface of the belt, where it drained into the weir sump.

Initial tests on this system in calm water proved that the flat surfaced belt worked as well as the sorbent belts at any speed or oil viscosity. Further testing in wave conditions proved that the belt conformed well to incoming waves and did not cause any significant amount of oil-water mixing. Testing over a wide range of speeds (2 fps to 8.5 fps) with oil viscosities ranging from 5 centipoise to 1000 centipoise, and with 6-inch and 8-inch waves, resulted in throughput efficiencies of 75 to 100 percent with almost pure oil being recovered (with careful control of weir height and pumping rate). Oil recovery rates for testing were equivalent to 150 gpm when scaled to a 4-foot wide fiber array.

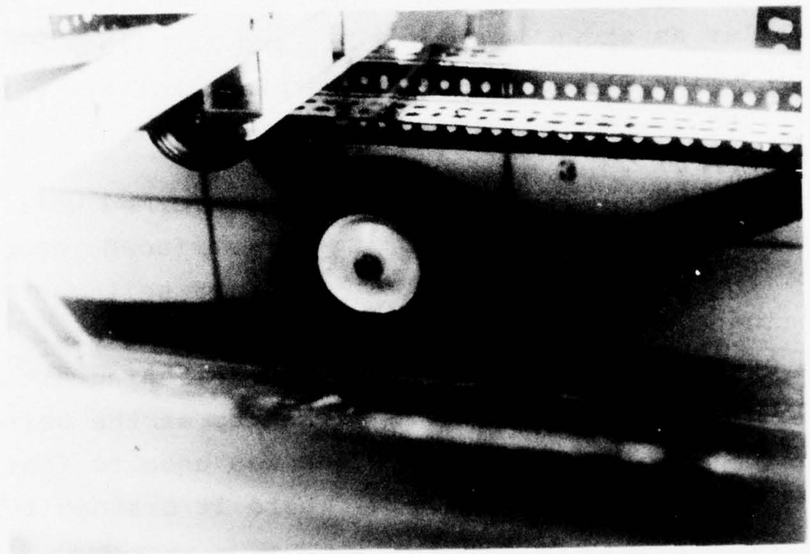


FIGURE 31 . SORBENT BELT GUIDE ROLLER

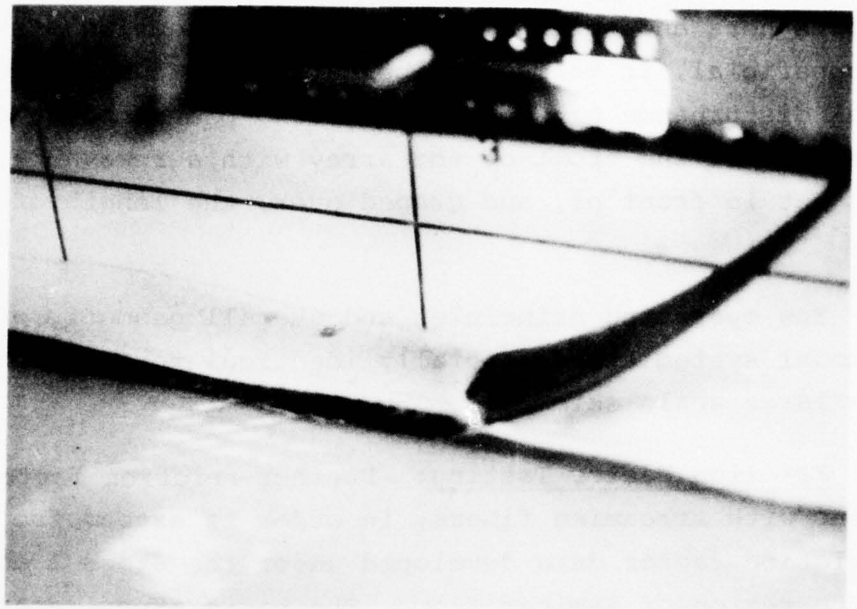


FIGURE 32. FINAL SMALL-SCALE BELT FRONT END

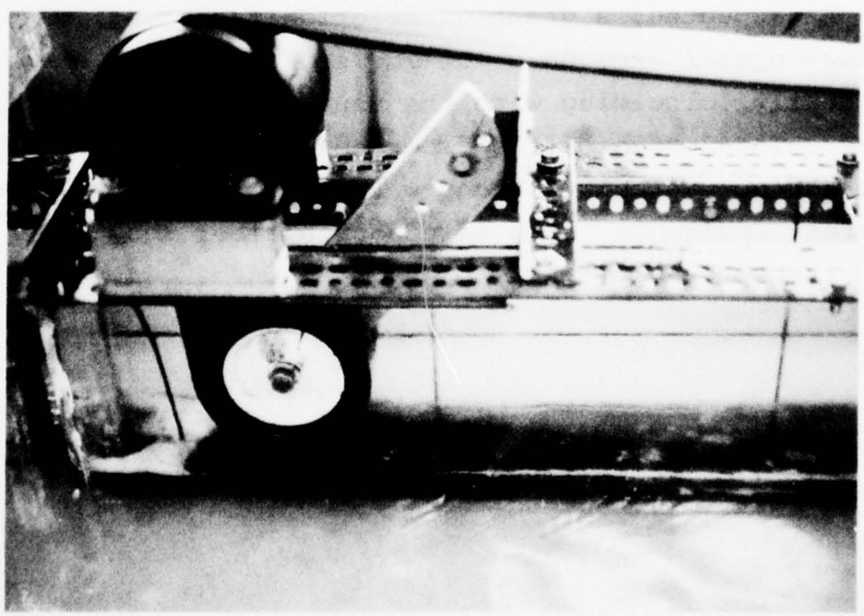


FIGURE 33. FINAL SMALL-SCALE BELT SYSTEM

Further testing was done with debris, and various types of debris nets and screens. The debris protection system proving most beneficial, in terms of fiber array and pump protection and minimal disturbance or blocking of flow, proved to be a coarse mesh screen at the front of the array with a removable, finer debris net in front of, and draped over, the length of the fiber array.

The operating principles and overall geometry of this final test model system are essentially identical to those employed in the large scale skimmer.

Friction Factor Testing: Further friction factor testing was done with streaming fibers, in order to extend the range of the friction factor data developed under the Stage I contract into the region of laminar flow. The basic experimental setup and procedure was generally identical to that of Stage I, and is described in detail in that final report. However, testing was done at lower flow rates and using a mineral oil (Gulf Security 53) instead of water, effectively lowering the Reynolds' numbers well into the region of laminar flow.

As expected, a graph of friction factor (f) versus Reynolds' number (Re) on a log-log scale plots on a 45 degree line, nearly coinciding with the usual pipe flow relationship, $f=16/Re$. The design of the fiber box length, however, is based on the assumption of turbulent water flow, since this would yield the safest design in terms of adequate fiber length.

3.5.2 Tow Tank Testing

To aid in designing the prototype hull and propulsion system, and to investigate the effects of the proposed bow shape, a model test program was conducted at the Davidson Laboratory. The tests revealed several methods to operate the skimmer more effectively, as well as a minor design change. Test data were generated which allow for proper sizing of the propulsion units, and for proper structural design. The appendix contains the Laboratory's detailed test report.

One objective of any test program is to watch for unanticipated problems and for areas to improve performance. There were three other specific objectives of the model test program at Davidson Laboratory:

- to verify that turbulence is not excessive in the fiber area, by observing the flow,
- to measure resistance, draft, and trim in calm water, and
- to measure resistance, heave, and pitch in irregular seas.

The table below lists the variables measured in order to meet all the objectives of the model test program.

Independent Variables	Dependent Variables
draft	flow pattern
static trim	drag
radii of gyration	pitch (trim)
location of center of gravity	heave (draft)
fiber box immersion	roll
heading	natural periods of heave, pitch, roll
speed	
water physical properties	

The next three paragraphs summarize the model test program. A discussion of the test results follows. The last part of this section is a description of the model and of the towing tank. For details of the model test program, see the appendix.

The skimmer worked effectively in the operating tests which covered a range of speeds from 2 to 5.5 knots, three sea states (calm water, and irregular seas of two significant wave heights, 15 and 25 inches) and two headings (head seas and following seas). In the highest sea state, high-speed performance was better in following seas than in head seas; the fibers could not dissipate all the energy of the occasional very large wave, consequently, it would break into the back wall of the fiber box. In large following seas the water surface over the fibers was nearly as quiescent as in the calm water tests.

Calm water resistance, draft, and trim were measured for the transit condition at speeds ranging from 3 to 12 knots and drafts of 2 and 3 feet. The rising and sinkage both bodily and in trim followed the same pattern as for a conventional ship hull; at low and moderate speeds there was a general sinkage and trim by the bow, while at higher speeds the movement of the bow is reversed and the model took on a decided squat.

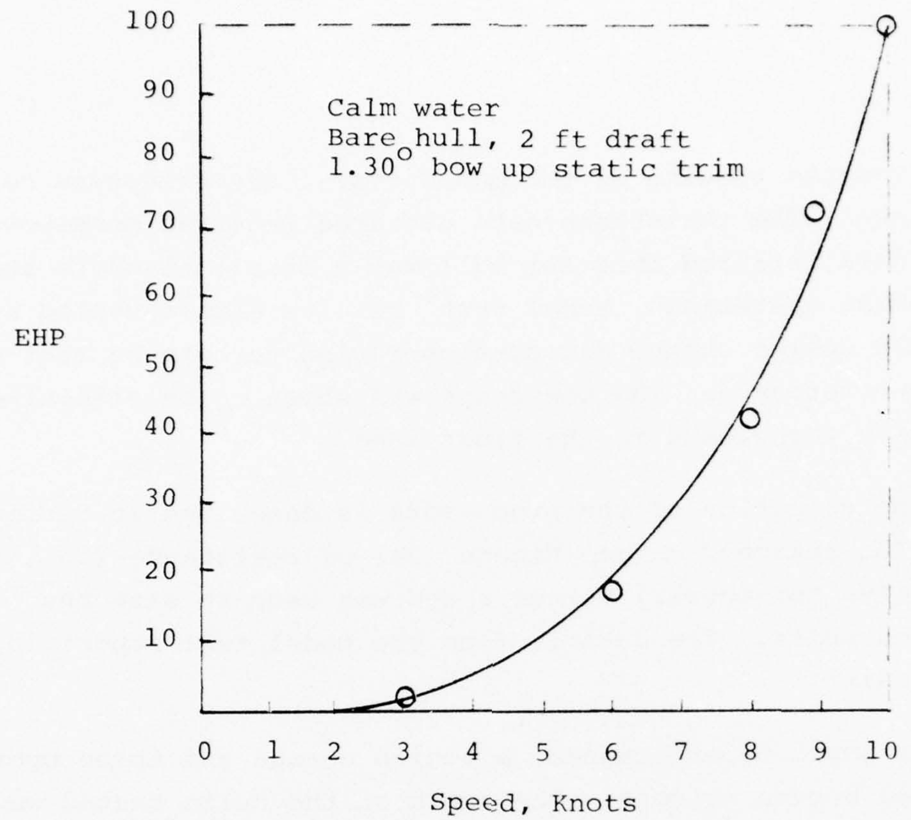
Resistance and motions were also measured for the transit condition in head seas of 25-inch significant wave height at speeds up to 13 knots. The decks stayed dry at speeds greater than 7 knots. Relative bow motion is reduced at high speeds because of the higher frequency of encounter, the result being both dry decks and a smaller incremental change in resistance between calm and rough water. These trends should continue beyond 13 knots, the limit imposed on maximum speed by the instrumentation.

From the results of the model tests, the prototype design was refined. The resistance data dictated required horsepower. Motions data verified that the hull was a stable platform suitable for skimming operations. Model test results also revealed a minor hull design change and some operating techniques that would improve performance. The bow shape was shown to be effective in reducing turbulance in the fiber area.

The selection of the propulsors is described in Section 4.2.6. The attached graph (Figure 34) of resistance (in terms of effective horsepower) versus speed was used to size the propulsion units. The data is from the model test report in the appendix.

To improve performance, a design change and three operating techniques became evident. The depth of the hulls tested was 5 feet from the bow to the stern (all dimensions are full-scale). Water would splash on the decks at moderate speeds in head seas at the transit draft of 2 feet. While wet decks are not a great problem, additional freeboard would prevent the waves from reaching the decks. Consequently, forecastles were added to the prototype design, increasing freeboard by 2 ft 8 in. Their effectiveness was demonstrated at OHMSETT; the forecastles of the large-scale model prevented 2-ft waves from wetting the decks.

A ballast system complete with pumps has been added to the prototype design for two reasons. First, drag can be reduced by nearly 10 percent at a speed of 10 kt at the transit draft by changing static trim. With the hull at even keel, drag at 10 kt was 3550 pounds. With a 1.35-degree bow-up static trim, this value reduces to 3260 pounds, a nine percent improvement. No optimization testing was performed, but a greater reduction in drag is probable.



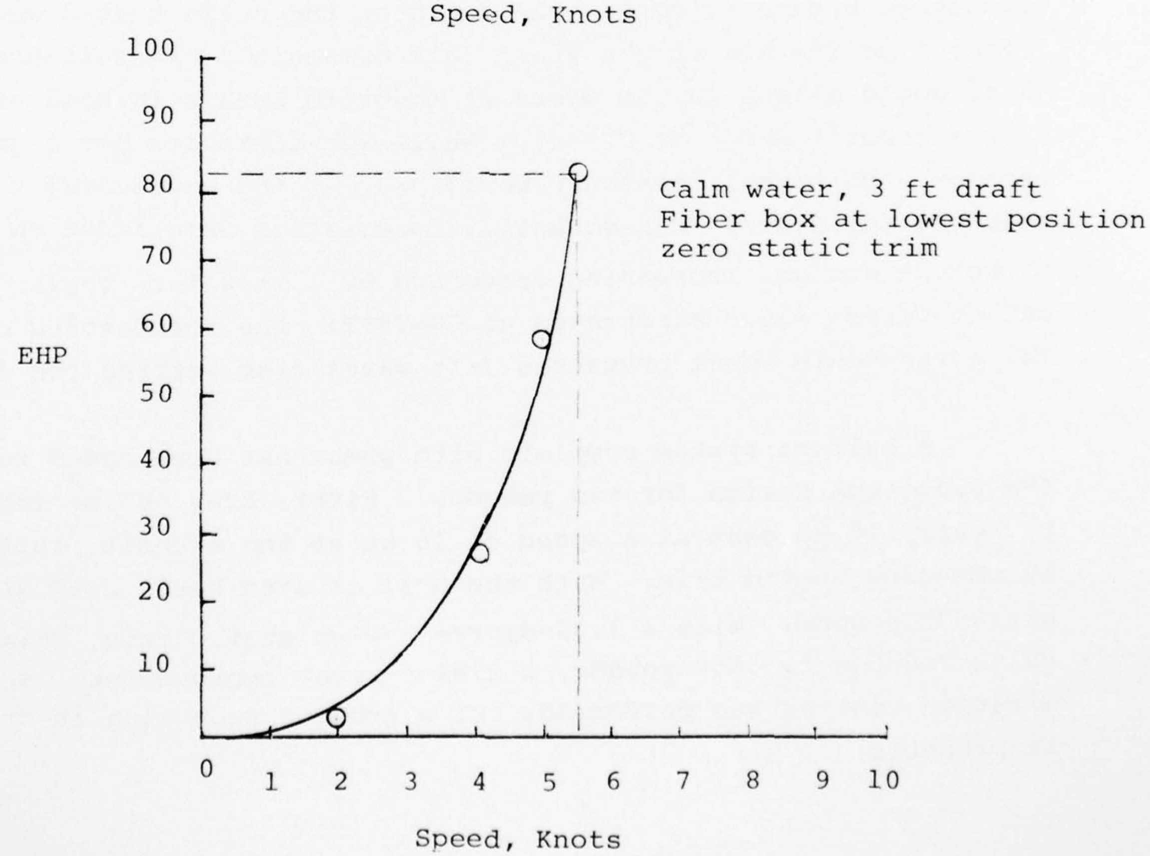


FIGURE 34. POWER REQUIREMENT PREDICTIONS

The second reason for the ballast system is to control trim while operating. Trim varies slightly both with speed and with displacement if the center of gravity remains fixed. Ballast maintains the fiber array at the desired trim in all conditions by moving the longitudinal center of gravity.

Another operating technique that should be employed whenever possible is to skim in following seas. The water surface remained quiescent in following seas, and the fibers conformed well to the waves. Matters were different in head seas. The water surface was reasonably quiescent until the occasional large wave broke against the back of the fiber box. Although the two test programs are not directly comparable, the same trend was apparent at OHMSETT where following seas oil recovery was more efficient than in head seas.

The model itself (Figure 35) was one-fifth scale. Principal specifications in full-scale dimensions were:

LOA	40 ft
beam	14 ft
demihull beam	3½ ft
depth	5 ft
operating draft	3 ft
operating displacement	45,000 lb
transit draft	2 ft
transit displacement	29,800 lb

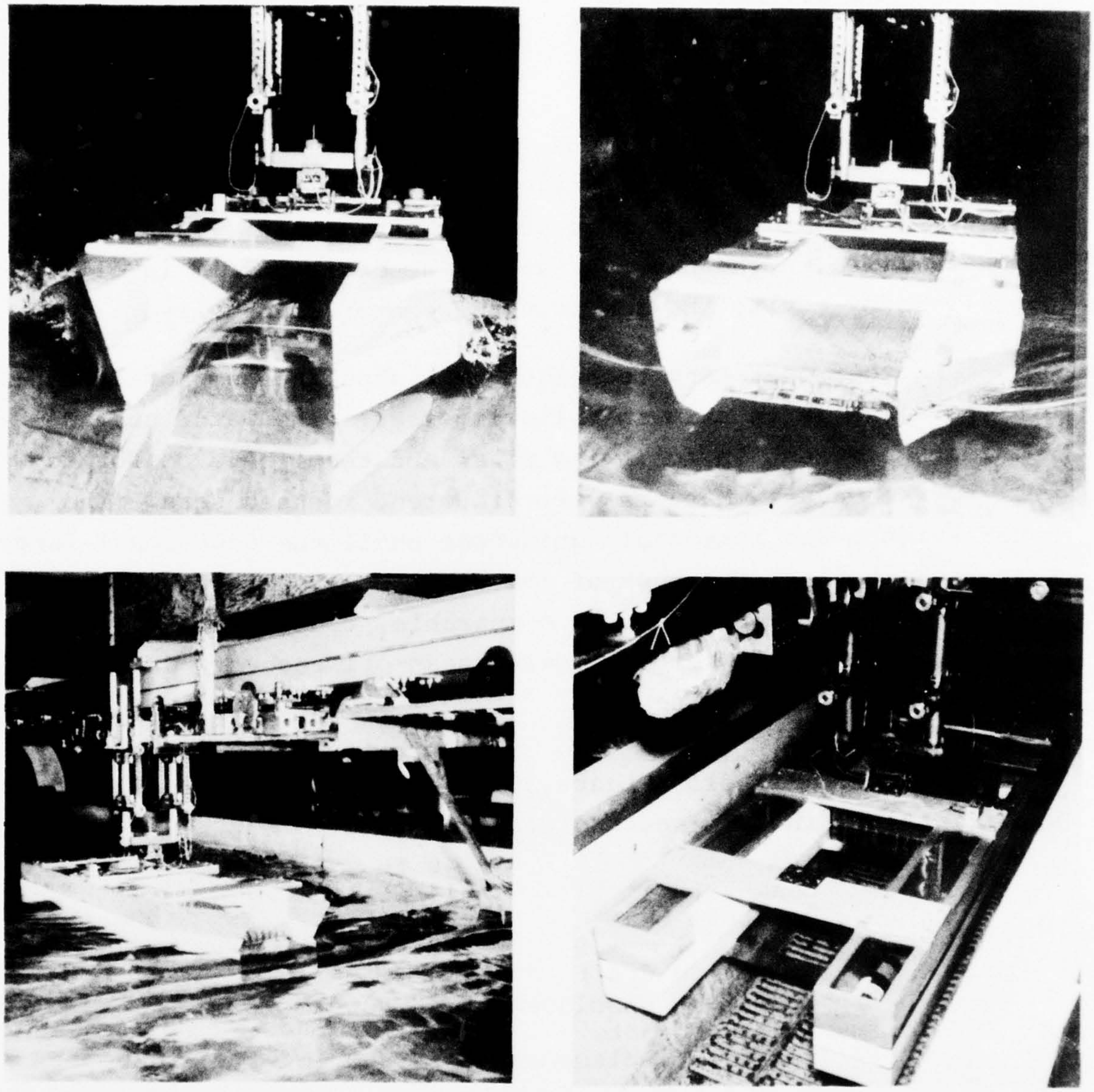


FIGURE 35
VIEWS OF MODEL TESTS AT DAVIDSON LABORATORY

A model fiber box was also provided for operating tests. The length, width, and depth of the fiber array were one-fifth scale just as the hulls were, but the effective diameter was not geometrically scaled. In the prototype, the effective diameter of 1.8 inch causes an incoming flow of 8 ft/sec to slow to zero over 15 ft, the fiber length (this value comes from predictions made in the Stage I report). In the model, the actual fiber length is 3 ft, and the design speed Froude-scales to 3.6 ft/sec. According to the same predictions used to choose the prototype effective diameter, a value of 0.83 inch was selected for the model.

All of the tests were conducted in Davidson Laboratory's Tank 3 which measures 313 ft long, 12 ft wide, and 5.5 ft deep.

In calm-water tests, signals from the instrumentation were transmitted from the towing carriage to signal conditioning units. These signals were then time-averaged by the tankside computer which displayed the results immediately after each run. Black-and-white pictures were taken of all runs to record the flow pattern between the hulls.

In wave tests, conditioned signals were stored on magnetic tape. The computer digitized the signals and evaluated them, again displaying the results immediately after each run. Selected segments of each test were photographed by a 16-mm slow motion movie camera.

AD-A041 315 SEAWARD INTERNATIONAL INC FALLS CHURCH VA F/G 13/2

DEVELOPMENT OF A STREAMING-FIBER OIL SPILL CONTROL SYSTEM, STAG--ETC(U)

DEC 76 R L BEACH, D W DURFEE, R J POWERS DOT-CG-40217-A

UNCLASSIFIED USCG-D-4-77 NL

2 OF 2

ADA

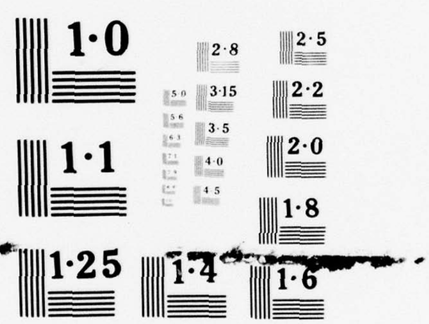
041315

END

DATE

FILMED

7-77



NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

4.0 PROTOTYPE DESIGN

The design goals for the prototype, as specified by the Coast Guard, are shown in Table 1 . To meet these goals, the development program described in this report was undertaken. The large-scale model test program showed, however, that certain goals were not attainable with the system as designed, and that modifications would be required in order to improve performance. In particular, performance in waves and in recovering the more viscous oils needs improvement.

Basically, the concept of slowing down the oil with an array of streaming fibers, and recovering the oil over a weir located at the end of the array, was shown to be sound. The problem with waves was that because the fibers were fixed in a rigid framework, neither the fibers nor the weir could conform to the wave profile; heavy losses and poor recovery occurred because of the mixing that took place as the waves passed through the fibers. The problem with viscous oils in high currents was that an endless sweeping belt was required to help transport the recovered oil pool towards the weir. In order for this to work properly, the fibers had to be lowered below the surface where the oil pool was then exposed to mixing from the unrestricted water jet flowing over the fibers. The belt concept was effective at lower velocities, however, where it prevented overthickening in the device.

It is felt that with certain design modifications the fiber concept can be made to work effectively in these presently adverse conditions. The modified system to be described in the following sections is, however, conceptual at this stage, and more development work would be required to prove the adequacy of the design.

TABLE 1
FAST CURRENT OIL RECOVERY
DESIGN GOALS

Areas of Operation

A. Bays, Harbors, Estuaries
B. Coastal Rivers
C. Coastal Waters

Operational Environment

Up to 6 knots current with optimal recovery in the 2 to 4-knot range and 2 feet confused sea with 20-knot winds.

Survival Environment

with current

A. 15 knots current with calm seas
B. 10 knots current with 4-foot waves and 20-knot winds

moored or adrift

A. 6-foot wave height with 40-knot wind for one week

Minimum Oil Thickness

0.04"

Oil Type

Complete range of oils including distillate fuel oil, residual fuel oil, and crude oil with optimum recovery to be in the range of 10 cs to 500 cs.

Sea Temperature

+28°F to 100°F

Air Temperature

0°F to 120°F

Mode of Operation

Moored, towed, and self-propelled

Transport from Central Storage to Nearest Port

One C-130 (39' x 9' x 7'10" LWH
with a maximum weight of 25,000 pounds each)

(Table 1 continued)

Transport from Nearest Port to Scene

A. Self-propelled
B. Towed by CG or commercial vessel equal to or greater than a CG 82-foot WPB
C. Carried on deck of CG 180-foot WLB or a comparable commercial vessel

Power Supply

Included

Fuel Supply

12-hour endurance

System Integrity

Impervious to the environment and oil

Cleanability

Easy to clean

System Support

A. Simple to assemble, install, load, launch, tend, refuel, maintain, operate, repair, and retrieve
B. Reliable
C. Assembly to be accomplished on scene in two hours

Control Function

System shall be capable of controlling oil so that it can be recovered.

Recovery Function

A. Throughput Efficiency $\geq$ 95%
B. Recovery Efficiency $\geq$ 75%
C. Recovery Rate up to and including 300 gpm

Debris Handling/Protection Function

Shall be able to handle a moderate size and amount of debris.

Pump and Transfer Function

Pump up to 300 gpm and not emulsify the oil.

Temporary Storage

Temporarily store 1400 gallons aboard and 500 long tons by external means.

4.1 Overall Features

In principle, the proposed prototype functions just like the OHMSETT skimmer; streaming fibers slow down the oil and water, and the oil is moved to a common point where it is picked up by a pump. The major differences are that the fibers and the fiber supports in the prototype are free-floating to conform to the wave profile, and oil transport to the common collection point is assisted by an oleophilic, porous belt sweeping beneath the fibers, rather than above.

The principal features of the revised concept are shown in Figure 36. The fibers are supported on support bars similar to the OHMSETT model, but the support bars and plates are attached to floats instead of to a rigid box. The front support section pivots on long arms attached to the hull, and the rear supports are attached to the front supports by similar pivoting arms. By varying the length of the arms the slack in the fibers can be adjusted to conform to the type of wave conditions encountered.

Beneath the fibers is an endless, rotating, porous belt with rollers attached to the front and rear fiber supports. At the rear fiber support, a squeeze roller compresses the belt, and the expressed oil floats to the top of the sump chamber where the oil is pumped off through floating suction heads. A weir opening in the plate behind the rear fibers can be adjusted for skimming light oil.

The fiber array is supported by a catamaran vessel, which can be disassembled and transported together with the necessary auxiliary equipment in a C-130 aircraft. Each demihull contains a diesel-driven propulsion unit, which are capable of propelling the assembled hull at 10 knots with the fiber array raised out of the water. The skimmer is also outfitted

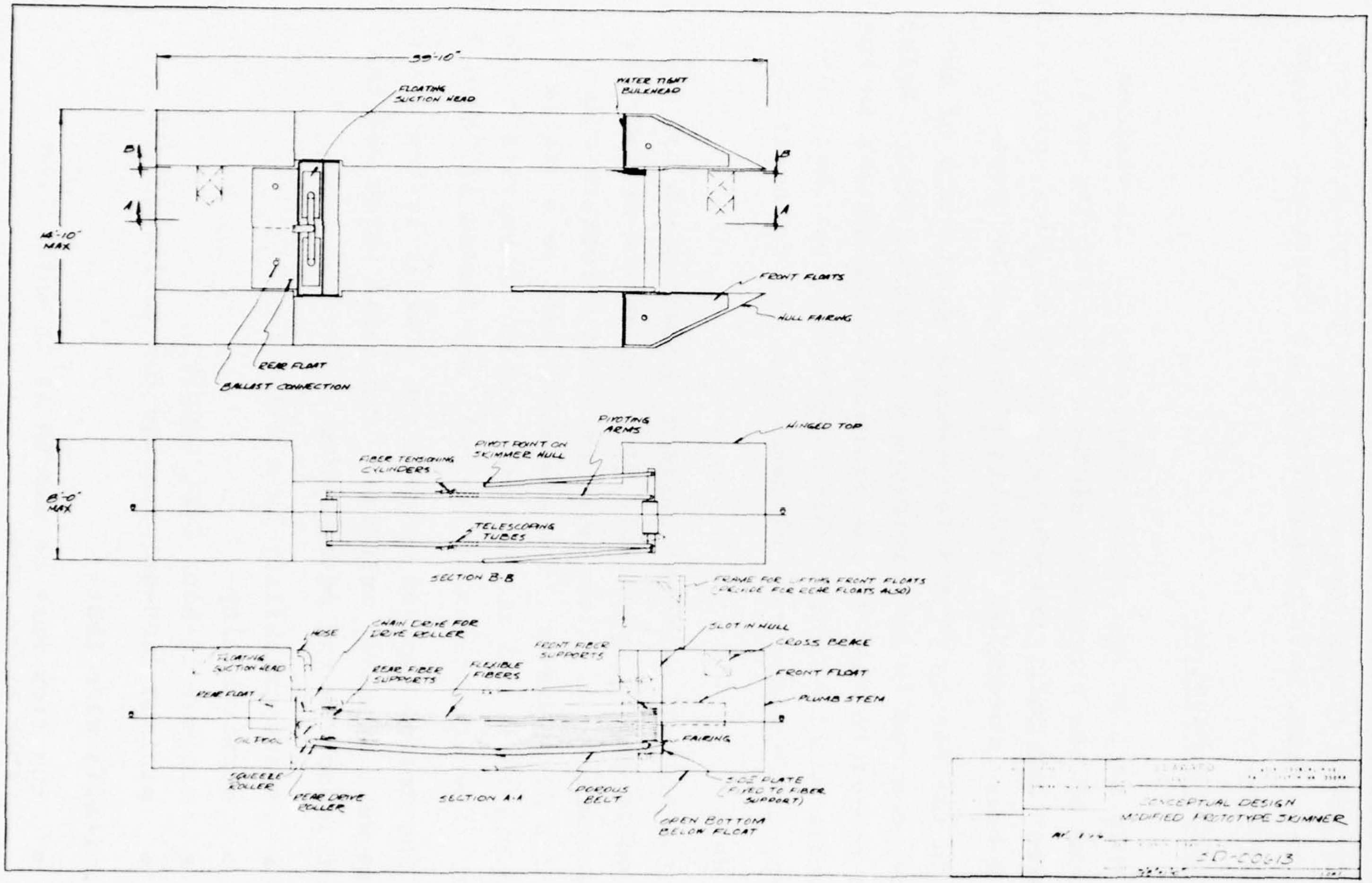


FIGURE 36. PROTOTYPE SKIMMER - MODIFIED DESIGN

with the necessary transfer pumps, oil storage tanks, hydraulic power system, controls, and other appurtanences. The entire system, when packaged for air transport, weighs 25,000 pounds.

4.2 Basic Subsystems

This section describes in more detail the various subsystems of the prototype skimmer, including the hull, fiber array and belt, transfer system, hydraulics, propulsion units, debris protection, and miscellaneous features.

In the design of the large-scale model, many of the features required in the prototype were anticipated. Reference is therefore made to the equipment descriptions in the large-scale model section, where applicable, so that only the major differences need be described in this section.

4.2.1 Hull

The hull of the fast-current skimmer meets all the design goals and is compatible with the entire system. It is a catamaran with a removable bridging structure which allows for disassembly. The assembled hull is a stable working platform, and it is strong enough to survive rough weather. Specifications of the hull are listed in Table 2 .

The design evolved to meet the overall system design goals as well as other criteria. The goals which had the greatest impact on the design were:

- transportability by a C-130
- survivability
- minimum 12-hour fuel supply
- minimum 1400-gal storage for collected oil

Other criteria were that:

- the flow must be smooth as it enters the fiber array, and
- the hull should be inexpensive, easy to build, and provide a stable working platform in seas.

TABLE 2
FAST-CURRENT SKIMMER HULL SPECIFICATIONS

LOA	38.5 ft
beam	14 ft
demihull beam	3.5 ft
depth	5 ft
operating draft	3 ft
operating displacement	44,700 lb
weight	12,000 lb
fuel capacity	170 gal
collected oil capacity	1,750 gal of 0.9 sp gr
ballast capacity	4,500 lb
maximum speed (fibers raised)	10 kt
maximum speed (fibers lowered)	6 kt

Early tests of one-third scale models of the bow section confirmed that the design would meet the operating criteria. The tests were conducted in the flume at Seaward's Clearbrook facility. The sharp-edged bows and wall sides provide for smooth flow into the fiber array (Figure 37).

Model tests of the prototype fast-current skimmer were conducted at Davidson Laboratory, Stevens Institute of Technology (Section 3.5.2).

The following description is for a hull designed to support a fiber box like the one used in the OHMSETT test model. However, the basic features of this hull would also be applicable for a wave-conforming fiber array as described briefly above (see also Section 4.2.2). The major differences for the wave-conforming design would be as follows:

1. The forward compartments would be open-bottomed to house the front fiber support flotation, and the bow stem would be plumb.
2. The size and spacing of the hull compartments would be changed to accommodate the loss of buoyancy forward (the oil storage capacity would still be a minimum of 1400 gallons).
3. A new (and simpler) lifting system for the fiber array would be provided.
4. The location of the cross-beams would be changed.

Basic Hull Features:

The demihulls are mirror images of each other. Each is divided into three watertight compartments. The aft compartment houses the machinery -- engine, propulsion unit, transfer pump and valving, fuel and hydraulic fluid tanks, and hydraulic

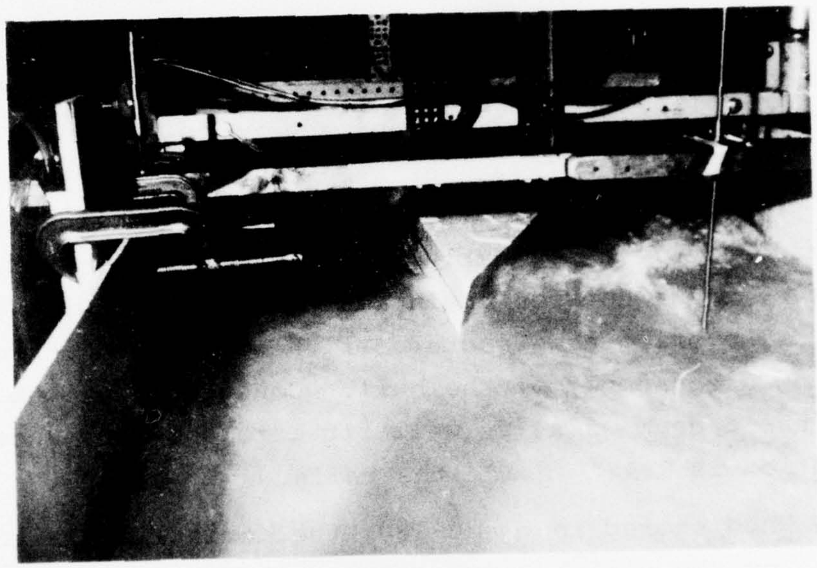


FIGURE 37
WALL-SIDED HULL SECTION IN FLUME TEST

circuit components. The compartment amidships is divided into four chambers by baffles; consequently, this compartment acts as a preliminary oil-water separator and stores the collected oil. The forward compartment is a trim tank with a baffle to reduce its free surface. These features are shown in Figure 38.

There are two minor differences between the demihulls. The starboard side contains the control console, and the port side has a foundation to support a small davit.

The vessel is constructed of marine-grade aluminum except for certain stainless steel fittings. The bridging structure consists of two 2-foot square box beams which bolt onto the demihulls. The assembled hull is strong enough to survive the environment described in the design goals. The structure is also nearly rigid; there is not enough relative motion between the hulls to interfere with the fiber array. The bridging structure of the catamaran is removable, allowing disassembly of the hull. Consequently, the vessel which has a beam of 14 ft will fit into a C-130, whose width limitation is 8'9½" inside the rails.

When stored in the C-130, the demihulls are together, resting on the pallet. The fiber array is on the deck of the hull, along with the auxiliaries. On scene, cranes separate the demihulls by 7 ft. The bridging structure is attached, and the fiber array is lowered into place. When the auxiliaries are brought aboard, the skimmer is ready to be launched.

The following calculations verify that the fuel supply and the oil storage capacity design goals are met.

The fuel tanks' capacity is 170 gallons, more than enough for twelve hours of operations. If each engine were to run at its peak output of 92 bhp for twelve hours, then they would consume

$$(2 \times 92 \text{ bhp}) \left(\frac{0.5 \text{ lb fuel}}{1 \text{ bhp - hr}}\right) (12 \text{ hr}) = 1100 \text{ lb of fuel, or } 170 \text{ gal.}$$

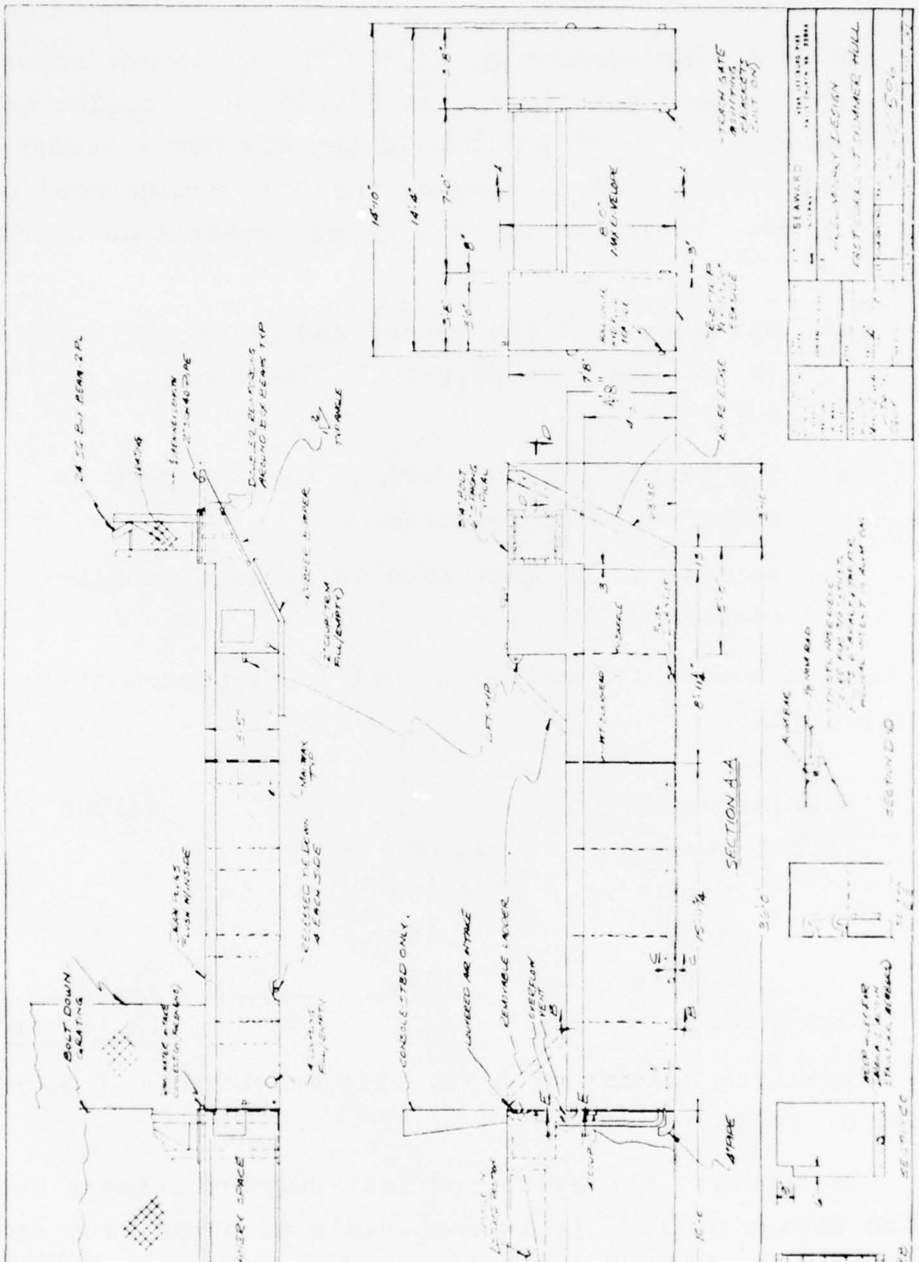


FIGURE 38. PROTOTYPE HULL - GENERAL FEATURES

Operating time is over fifteen hours at the engines' continuous rating of 73 bhp.

With a displacement of 44,700 lb at its operating draft, the skimmer can store over 13,000 lb of collected oil, or more than 1,700 gallons if the oil has a specific gravity of 0.90. This is greater than the design goal of 1400 gallons. To arrive at this value, several assumptions were made:

- The weight of the vessel and all auxiliaries is no more than 25,000 lb (the capacity of a C-130)
- Six people are on board (a minimum crew of three would be required)
- Ballast is no more than 10 percent of displacement.

The maximum weight for collected oil is displacement less all other weights:

Displacement			44,700 lb
Less:	vessel	25,000 lb	
	fuel	1,100	
	crew	1,000	
	ballast	4,500	31,600
Oil Storage			13,100 lb

With a specific gravity of 0.90, this weight of oil occupies a volume of 1,740 gallons.

In summary, the prototype fast-current skimmer hull meets all the design goals. It is compatible with the rest of the system, and it can be stored in most C-130s with all the auxiliaries. However, as designed, the skimmer will not fit in Coast Guard HC-130s that are equipped with electronic equipment in the forward overhead. Model tests were invaluable in designing the hull, as well as the rest of the system.

4.2.2 Fiber Array

For a calm-water prototype similar to the OHMSETT model, all of the basic features of the large-scale model fiber box would be incorporated into the design. Only the transverse members, such as the fiber support plates and bottom cross-members, would be enlarged slightly to provide the strength needed for the wider 7-foot span. An improved method of suspending the fiber box on the Acme nuts would also be incorporated as discussed previously. The drive shafts would be recessed into the hulls to provide a minimum hull envelope for packing. Separate side-wall extensions for the box would also be provided, so the box height could be reduced for storage in the plane.

For a wave-conforming fiber array, however, a considerably different design is required. These design features are discussed below.

The fiber type (nylon), diameter, and spacing would probably remain the same, although additional development tests would have to be run to confirm this. The fibers would probably be longer to increase the design speed and also to allow more safety factor for surges. Approximately 2 feet of fiber depth would be provided, but with only about 1 foot suspended below the surface. To decrease weight, fiber support bars made of fiberglass would be considered. The top plates would not need the milled slots because the plates would always be above the surface. Other than these changes, the basic fiber construction method would be the same as the large-scale model.

The front fiber support plates could be disconnected from the floats, to enable packing in a C-130. The floats would be lightweight aluminum containers, which could be ballasted to change the fiber depth. Sufficient waterplane area would be provided to ensure wave conformance within a few inches, in up to 2-foot harbor waves.

The front fiber support would be held in place both longitudinally and transversely by pivoting arms connected to the hull. Because the arms are parallel, the fiber support bars will always remain perpendicular to the deck as the floats move up and down in a large-radius arc. Similar arms connecting the rear support section to the front support section will keep these two sections parallel to each other. Both sets of arms will be under column loading during operation and will be sized to avoid buckling.

Each front-to-back arm will have a sliding joint in it so that its length can be changed to adjust the amount of fiber sag. To ensure equal adjustment in each of the four arms, the lengths will be controlled by hydraulic cylinders. Each cylinder will be double-ended and plumbed in series, so that the fluid displaced by the first cylinder will displace the second cylinder an identical length, and so on. An adjustment range of only about 6 inches will provide enough fiber slack to handle the largest waves likely to be encountered in a 2-foot harbor chop.

An alternative to the above design would be to provide a free-floating but rigid framework to support the front and rear fibers, and allow the front floats to ride up and down on casters, which in turn would ride on the skimmer hull itself. The relative merits of these two approaches need further investigation.

Keeping the fiber array approximately one-third to one-half out of the water is advantageous in several ways:

1. Not as much fiber depth is needed to slow down the oil and water because the fibers would tend to follow the wave profile and stay a constant distance below the surface.

2. With the porous oleophilic belt located below the fibers, local overthickening will not result in catastrophic losses out the bottom.

3. Because not as much water would be entering the array, the vertical velocity components out the bottom would be less (important to minimize the belt pressure drop).

4. Having additional fibers available from above the surface when the fibers are slack will help to avoid a void region in front of the rear fiber supports (as observed in Stage I testing).

5. The best throughput efficiency observed during OHMSETT tests occurred when the top plate of the fibers was out of the water.

The principal disadvantages of elevated fibers are that local overthickening could not be prevented, and debris would tend to collect on the front fiber supports. However, with the belt located below the fibers to catch oil coming through the bottom, local overthickening will not cause the loss it would ordinarily. In fact, the principal means to recover viscous oil would be to permit it to overthicken and collect on the belt, and then be carried to the back for recovery. The debris problem would be minimized because better debris protection can be provided (for example, smaller screens) with some assurance that mixed oil could be trapped in the belt.

The rear fiber support section would be constructed similar to the front section. The flotation in this case would be located behind the weir/sump area, where it would not interfere with the flow. Location of the weir lip near the vessel's center of buoyancy is not necessary, as the entire weir-fiber assembly is essentially independent of the vessel motion.

For high speed transit to or from the spill site, the fiber array would be lifted clear of the water, using ordinary tackle supported from overhead gallows or A-frames. The top

support arms would have to be disconnected from the hull in this case. At the front floats, a hinged deck covering (grating) would be provided so the flotation could be removed. Hoses to each flotation tank would be connected to a bi-directional water pump, so that ballast could be changed as desired. A two-compartment rear flotation tank would be provided so that the weir could be leveled. By ballasting all of the tanks so that the fibers were sufficiently under water, low-speed skimming of any oil could be performed using the weir opening to provide oil to the pick-up heads.

4.2.3 Belt System

For a calm-water prototype similar to the final OHMSETT model, all of the system features incorporated into the large-scale model would also be included in the prototype, with the exception of the rear roller height adjustment, which would not be needed. Two belts would probably be used instead of one, to accommodate the 7-foot span.

A revised design incorporating a full-width, porous, oleophilic, rotating belt underneath the fibers would be quite different, however, both functionally and mechanically. The exact type of belt used could only be determined after performing a series of development tests. Several desirable features of the belt are listed below:

1. The belt should be highly oleophilic to absorb both light and heavy oils, and to hold them in the belt while water passes through.
2. Porosity should be high enough to permit easy passage of the water through the belt (low pressure drop).

3. The material should possess a high volumetric oil retention capacity.

4. The belt should have good strength in a thin section (1/2 to 1-inch thick).

5. Good durability under repeated squeezing is required.

6. Conformance to wave profiles (when slack) should match the fibers.

7. Materials shall be resistant to weather, water, and all types of oils.

The material which meets most of these requirements is an open-celled reticulated polyurethane foam, similar to the type discussed by Moses and Blackstone[7]. The endless belt would be supported on two rollers, at least one of which would be driven by a hydraulic motor. The forward roller would be located immediately below the forward fiber support and the rear roller would be located under the oil collection sump, behind the rear fiber array. A tensioned squeeze roller behind the rear belt roller would be used to express the oil from the belt, where it would float to the surface for recovery by the suction pickup heads.

The belt would rotate with the side nearest the fibers (top side) moving aft, and therefore downward through the rear drive roller and the squeeze roller. Netting on each side of the belt would be used to provide structural strength. To ensure a positive drive, a lightweight roller chain or a Velcro traction mechanism would be used. With the belt supported between the front and rear fiber supports, any adjustments to the fiber sag would also affect the belt sag. Wave conformance would therefore be about the same as for the fibers. Since both rollers would have to turn simultaneously, a synchronized drive system for the front and rear rollers may be required.

One characteristic of the streaming fiber concept is that as the incoming horizontal velocity is slowed down, the water is forced out gradually along the whole length of the bottom. Equations presented in the Stage I Final Report[1] show that for a homogeneous fluid being slowed in a fiber array, the vertical velocity components are highest at the entrance to the device, and almost linearly taper off to zero at the end (or where the horizontal velocity component also reaches zero). The longer the fiber array is with respect to the depth of fibers, the lower the vertical velocities are along the bottom.

Another important characteristic is that the oil losses tend to occur towards the rear of the device rather than in the front. In fact, Stage I data indicated that the oil starts to thicken and form a headwave only after the horizontal water phase velocity has been slowed to around 1 foot per second (see Section 3.2; data was for d_e=1.3 inches). Vertical velocity components where the headwave starts to form and where losses would tend to be most severe, could therefore be quite low.

Data for typical low-density reticulated polyurethane foams[7] show that with water flow the pressure drop is very low, and appears to vary nearly linearly with velocity, at velocities below approximately 2 fps. For example, with a 1-inch thickness of 10-ppi foam the pressure drop at 1 fps is approximately 3 inches of water. Through proper design of the fiber array (high length to depth ratio and large d_e), velocities and pressure drops through the belt can be kept to very low values. This feature is important for two reasons; first, with low pressure drop through the belt, the velocity distribution throughout the fiber array is not as likely to be affected, and secondly, low velocities through the belt will be less likely to dislodge oil absorbed at the interstitial nodes in the foam.

Some oil may enter the top side of the belt as it progresses towards the squeeze rollers, but be forced through before it gets there. However, the returning side that it encounters next will have been squeezed relatively free of oil, with plenty of absorption sites available for oil collection. This counter-current contacting is another desirable feature of the belt system.

The front belt roller would be covered by a fairing to protect it from debris. As the fairing also acts as blockage, its design is important. Preferably it would be designed to deflect the water downward with a straight flow over the top (much like the bow shape performs); but as this would tend to create an adverse lift force, the fairing may have to be designed more as a wedge with balanced lifting surfaces. Besides the fairing, the fibers themselves provide debris protection for the top side of the belt. A coarse screen across the bottom of the hulls will protect the bottom side of the belt.

Use of a bottom belt may extend or remove one of the possibly limiting features of the fiber concept itself, that of excessive entrainment losses at inlet velocities greater than about 8 fps. With something to catch the oil after it leaves the fiber array, the velocity range of the concept may be extended considerably. In fact, many limitations of the present fiber system design may be diminished, as long as something is available to catch the oil as it leaves the fibers.

4.2.4 Transfer Pumping System

To provide a 300-gpm transfer pumping system, two pumps identical to those used in the OHMSETT model would be provided. Also, the same motor, coupling, and valve arrangement (See Figure 19) would be used, as these proved satisfactory in OHMSETT testing. Using a 2000-psig hydraulic system, a nominal discharge pressure of 50 psi can be attained, which is sufficient to transfer 10,000-SSU oil through the piping and

hoses to the oil storage tanks or to external oil storage bags (Section 4.3.1). Each demihull will contain one of the systems in its machinery compartment. A larger capacity hydraulic flow control valve would be provided, to enable faster pumping speeds while pumping low viscosity oil, or oil-in-water mixtures.

Pumping out of the sump area will involve the use of a semi-floating pickup head, constructed with a large mouth area on the underside to minimize water pickup. Figure 36 shows two heads with one common discharge hose, which would branch into individual lines to each pump (not shown). Completely independent pickup heads piped individually to each pump is an alternative design. The heads would not be completely free floating, as stiffness in the hoses imparts a certain amount of rigidity to the system; however, as long as the mouth openings are underwater sufficiently, and a deep enough pool of oil is present, the oil could be recovered. An oil-water interface sensor would be installed in the sump to monitor the oil level.

Oil flow to the sump could also occur through a weir opening in the plate behind the fibers. This opening would function more as a window than a weir, as ordinarily (with viscous oils) it would be closed to keep the oil expressed from the squeeze rollers from flowing back into the fiber area. With light oils it would be opened, as a thick layer of light oil can then be built up merely by flow through the fibers.

Oil discharged from the pumps would be directed into the forward end of the compartmentized hull storage tanks. As the level built up, the first (forward) compartment would act as an oil-water separator; any oil not separated would flow into the second compartment where another chance at separation would occur. After the compartments were filled with

liquid, the water in the last (aft) compartment would overflow, but as it would be relatively free of entrained oil, oil losses would be minimized. The tanks would be vented at a point high enough to assure water overflow before oil overflow. The total tank capacity as shown in Figure 38 is larger than 1700 gallons, but the same separating scheme would be used for smaller tanks.

4.2.5 Hydraulics

Most of the components and circuits utilized in the OHMSETT model were satisfactory and would be used in the prototype (see Figure 20). Major changes are described below:

1. For a floating fiber array, the jack-screw elevating circuit would be eliminated. Lifting of the fiber array and floats would be performed by hand, using conventional tackle.

2. A piped-in hull and float ballasting system would be installed, which would be powered off the hydraulic system. The circuit for each demihull would consist of a directional control valve, flow control valve, and hydraulic motor, driving a positive displacement water pump, which was self-priming in either direction of flow. Flow to and from the various tanks would be controlled by a valve manifold in the water piping. The same pump would also provide wash water for system cleanup after an operation. As this circuit would see only intermittent use, it would not affect sizing of the hydraulic pumps.

3. For redundancy, identical port and starboard circuits would be provided. Cross-piping of the hydraulics could be done when necessary. Although only one belt drive would be provided, each circuit would be sized and equipped to supply it.

4. A porous belt system would probably require a different pressure and flow combination than an above-water smooth belt, but the only effect on the hydraulic circuit would be from a slight sizing difference in the components. Porous belt speeds may range to 8 fps, whereas smooth belt speeds would range to only about 4 fps.

5. Reservoirs, coolers, and other hydraulic appurtanences would be duplicated in each hull.

4.2.6 Propulsion

The propulsion system proposed for the prototype fast-current skimmer is two inboard engine, outdrive units. Each demihull will contain a complete outdrive system, with controls located on the starboard console. Power is provided by diesel engines.

Stewart & Stevenson's model DD-3-53-MN dieseldrive system is one commercial product that is suitable to propel the fast-current skimmer, with one small modification: the vertical drive shaft must be extended to accommodate the 3-foot operating draft. This can be done by the manufacturer. Table 3 lists the principal specifications of this particular outdrive system. The various considerations that went into selection of the propulsion system are discussed below.

The main features of the propulsion system that are desired are:

- dependability and durability
- safety
- compact size
- light weight
- maneuverability
- efficiency

TABLE 3

SPECIFICATIONS

STEWART & STEVENSON DIESELDRIVE MODEL DD-3-53-MN

engine model	GM 3-53, lightened and modified by Stewart & Stevenson
engine type	2-cycle diesel
number of cylinders	3
bore and stroke	3.875 in x 4.5 in
effective displacement	318 in^3
rated horsepower	115 bhp @ 2800 rpm
maximum torque	242 ft. lb. @ 1700 rpm
compression ratio	21:1
outdrive steering type	side arm
steering angle	30 degrees each direction
reverse	in-drive clutch
overall system width	26 in.
total system weight	1100 lb, per unit

- compatibility with the other systems of the skimmer
- suitability for transport by a C-130

Given this set of desirable features, there is not a great range of alternatives for the propulsion system. Axial-flow propellers are more efficient and compact than other propulsors, such as pump-jets and vertical-axis propellers. Supercavitating or tandem propellers need not be considered for the speed and thrust requirements of the skimmer. Among the many available energy sources, only piston engines are practicable. Therefore, the alternatives are type of drive and type of engine:

Type of Drive	Type of Engine
inboard	gasoline
outboard	diesel
outdrive	

For safety, reliability, and efficiency, the better choice for the engine is a diesel. This has been proven over many years of marine experience. Diesels are also more suited for the fast-current skimmer because of the intermittent use it is likely to encounter.

The best type of drive for this application is the outdrive. Inboards are less complex and perhaps lighter, but when integrated into the skimmer, transportability in a C-130 becomes much more difficult. The propeller and rudder of an inboard drive have fixed positions relative to the demihull. Since they extend below the keel, they are vulnerable, and they increase the envelope dimensions of the hull. Regarding outboards, not only are diesel-driven units heavier than outdrives,but they also increase envelope dimensions -- typically the engine is mounted on deck.

Outdrive units are highly maneuverable, compact, and lightweight. With an outdrive, the vertical envelope dimension of the hull (in storage) is its depth, since nothing extends above or below. This is true since in storage the drive unit lifts above the keel, and the engine is mounted inside the hull. Another advantage is that when stored in a C-130, the drive units can lift and extend into the space above the rear cargo door, a space not included in the longitudinal envelope dimension of 40 ft.

The other question relating to propulsion is the power requirement. This can be accurately estimated from the model test results (Section 3.5.2) and the design goals:

speed to site	10 kt
operating speed	up to 6 kt

Propulsive efficiency is defined as the ratio of useful work expended per unit time to power input:

$$\eta = \frac{ehp}{bhp} \qquad (6)$$

Rearranging this formula, brake horsepower for each of the two engines can be expressed in terms of effective horsepower and efficiency:

$$bhp = \frac{ehp}{2\eta} \qquad (7)$$

Propulsive efficiency should be at least 0.65 for the prototype fast-current skimmer. This is based both on experience and on data which indicate that the range of propulsive efficiency for the majority of twin-screwed surface vessels is 0.60 to 0.70. Effective horsepower has been determined from the model tests at Davidson Laboratory.

Condition	Speed (kt)	ehp
in transit, 2-ft draft, zero static trim	10	109
in transit, 2-ft draft, 1.35 degree bow-up static trim	10	100
operating, 3-ft draft, box at normal depth	5.5	60.9
operating, 3-ft draft, box 8 3/4 in. below normal depth	5.5	82.5

The value to be used in sizing the diesel engines is an effective horsepower of 100 hp. This is based on the fact that there will be means to control trim on the prototype skimmer (Section 4.2.1).

Therefore, by substituting the proper values into the formula for brake horsepower, the minimum power requirement is obtained:

$$\text{bhp} = \frac{\text{ehp}}{2\eta} = \frac{100}{(2)(0.65)} = 77 \text{ hp} \quad \text{(each of two engines)}$$

Diesel engines the size of GM model 3-53 are suitable for this application. With a maximum rating of 115 bhp (Stewart & Stevenson), they have ample but not excessive reserve power. Furthermore, their dimensions and weight are well suited to the prototype fast-current skimmer.

One acceptable propulsion system is Stewart & Stevenson's model DD-3-53-MN. This manufacturer lightens the GM 3-53 diesel engine and couples an outdrive system to it. Specifications are listed in Table 3 .

An alternative to an off-the-shelf system is a diesel-hydraulic propulsion system specifically designed for the fast-current skimmer. Flexibility is the advantage of such a system. Since power is transmitted through hydraulic hoses, the diesel engine and hydraulic pump can be located without regard to the location of the hydraulic motor and propeller. For storage, the propeller and motor can be easily removed. The motor would be mounted on an azimuthing strut. Small hydraulic motors or cylinders would turn these struts and consequently steer the skimmer.

All the components of this special design hydraulic propulsion system are standard, proven items. Even though this design is one of a kind, there is no anticipated problem. One disadvantage, however, is a loss in efficiency. The prime mover needs to provide approximately 20 percent more power to compensate for increased transmission losses.

Of all the alternatives, a diesel-powered outdrive system is the best propulsion system for the fast-current skimmer. It is safe and reliable, compact, and very maneuverable. The two most attractive means to transmit propulsive power are mechancial drive shafts and hydraulics.

4.2.7 Other Features

Protection against debris would be provided by an array of rigid bars, and also by a coarse screen placed just in front of the fibers. The bars would protect against larger debris which could damage the equipment,and the coarse screen would keep seaweed, paper, and similar debris from clogging the fibers. Both devices would be removable, and could also be pivoted upward to aid in hand cleaning. A certain amount of oil-water mixing at the screen could be tolerated with the

porous belt installed below the fibers, because any mixed oil would tend to be caught in the belt.

The skimmer would be equipped with standard marine safety equipment, such as running lights, spotlights, etc., and all instrumentation necessary to monitor the engine and other subsystems.

4.3 Auxiliary Systems

In addition to the basic hull and on-board oil skimming equipment, certain other components are needed to enhance oil skimming performance in particular situations, and to meet the design goals. These include the design requirements to provide external oil storage, and an air transport capability. For operations in rivers, where the skimmer may have to be moored with diverting booms feeding oil into its mouth, special equipment is also required. Although much of this equipment would not be provided as part of the prototype package (except for air transport), a discussion of the operational and design considerations is necessary.

4.3.1 External Oil Storage and Hoses

The capacity of recovered oil aboard the fast-current prototype is approximately 1750 gallons. If the vessel is recovering oil near its limit of 300 gpm, then it will take only six minutes to fill the storage tanks. In order to provide for extended operations, some means of external oil storage is necessary. This requirement presents little problem when the skimmer is moored in a swift river, since tank trucks or barges should be available to serve as storage. However, matters are more difficult offshore.

An attractive solution for offshore oil storage is floating, towable, pillow-type tanks. These tanks are rugged flexible bags made of oil-resistant materials. They can be easily towed full by the skimmer, and when empty they fold into a small package. There are at least four manufacturers of the bags as standard commercial items, which are recommended for use with the prototype fast-current skimmer:

Manufacturer	Product Trademark
Dunlop	Dracone
Kepner Plastics Fabricators	Sea Container
Superflexit	Caiman
Uniroyal	--

Capacities range from 600 gallons to many thousands of gallons. Recommended capacities are 5,000 gallons or less for ease of storage and handling. All the manufacturers listed above, except Dunlop, currently produce tanks in this size range as standard commercial items.

Operations with the bags fall into three phases:

1. attachment to skimmer's storage tanks
2. filling
3. disposition of bag

There are alternative procedures to perform each phase.

The empty bag either can be stowed on the skimmer or can be transferred to it by another vessel. When the empty bag is stowed on the skimmer, the small davit on the port demihull lifts the bag and places it into the water after the hose and tow line are attached. The bag is now ready for the second phase -- filling. On the other hand, when the bag is brought to the skimmer, attachment of the hose and line can be accomplished in the water.

All of the products listed above can be filled with the skimmer moving at any speed from at rest to its maximum operational speed of 6 kt.

To dispose of the bag, the crew needs only to disconnect the hose and tow line. The bag can then be towed by another vessel to the disposal site, or alternatively, it can be left moored for later recovery.

The following scenario depicts one example of an oil recovery operation offshore. Besides the fast-current skimmer, there is a barge, a utility boat, and three storage bags on scene.

The fast-current skimmer is making long passes through the oil spill, transferring collected oil from the storage tanks to a towed bag while skimming at the same time. There is little water being transferred because the recovery efficiency is high and because the storage tanks act as an oil-water separator. Meanwhile, the utility boat is approaching the skimmer with a bag that was just emptied into the barge. While turning to pass through the slick again, the skimmer stops to exchange its full bag for the empty. The barge's crew has just emptied bag number three and is awaiting the next full one. This scene repeats itself until the entire spill is recovered; the utility boat shuttles full bags from the skimmer to the barge, and empty bags back.

Regarding the hoses used in this operation, they are all flexible transfer hoses, 4 inches in diameter. They meet military specification MIL-H-82127(MC), "Hose assembly, rubber (synthetic); fuel, discharge, lightweight." The cam-action couplings -- compatible with the fittings on the skimmer, bags, and barge -- assure rapid, easy connections and disconnections.

4.3.2 Boom Attachment - Boom Recommendations

Where use of diverting booms is desirable with the skimmer, a set of special boom adaptor plates, shown previously in Figure 2 , would be used. These adaptor plates could be quickly fitted to the skimmer and would provide a vertical attachment point with minimal blockage or disturbance to flow. The boom connectors provided with the adaptors and recommended for the diverting boom would be the present design, standard Navy end connectors.

The diverting boom used with the skimmer should have good stability in currents, adequate strength and reserve buoyancy, and should be smooth and streamlined in shape so as to minimize disturbance to flow and snagging on debris. In

order to minimize the drag in currents, the boom should have the minimum draft required to divert oil under the wave conditions present. A medium draft boom, such as the B. F. Goodrich 18-inch Seaboom could be used in rivers and bays, with some limited use in open waters. For most open sea use, or in higher wave conditions, a deeper draft boom, such as the 36-inch Seaboom would be recommended. In wave situations, the boom would have to be decoupled from the hull motions by connecting it to the adaptor plate with a two-part rope bridle.

In any case, the catenary of the boom should be limited, so that the water velocity at any point normal to the boom would not exceed 1 knot. Where using long boom sections in stationary mooring situations, such as in a river, it is recommended that the diverting boom be moored at several points along its length in order to limit the catenary sag of the boom.

4.3.3 Mooring

For use in a fast-moving current or river where the skimmer is to be located in a stationary position, the skimmer should be moored at two points using anchors or shore mooring points.

Tow tank studies on the model hull indicate that in a 5½-knot current the drag on the skimmer would be approximately 5000 pounds. Based on this drag value, two mooring lines of 3-inch circumference nylon or dacron line would be recommended. For sandy bottom conditions a 50-pound Danforth anchor would be recommended at each mooring point with a 7 to 1 scope in the mooring line. Crown buoys are recommended for accurate positioning and retrieval of the anchor. Mooring lines for the boom should be similar to the skimmer to provide compatible surge compliance.

A typical proposed mooring configuration for use in a narrow river is shown in the Stage I final report. However,

the actual mooring and configuration to be used will depend upon operating conditions, location, current speed, type of bottom, and other factors.

Where long diverting boom lengths are used, a series of oil boom moorings are recommended along the length of the boom. Consisting of a small Danforth anchor, cable length, and mooring float, these moorings should be used for positioning of the boom and to prevent excessive catenary in the boom over long spans.

4.3.4 Air Transport

For transport in a C-130 aircraft, the prototype skimmer will be provided with a special pallet, such as Metric Systems Corporation's A/E 29 H-1 modular aluminum cargo platform, which is adaptable to the Dash 4A cargo rail system installed in certain existing Coast Guard planes. The cargo package will be provided with the necessary strapping and tie downs, adequate for the maximum accelerations encountered in the C-130 (4 G's in the forward direction assuming no passengers are carried forward of the load, 1½ G's sideways, and 2 G's in the other directions).

A drawing showing the overall arrangement of the skimmer sections and hardware as loaded on the C-130 aircraft, is shown in Figure 39. As shown, the skimmer must be broken down and rearranged into a more compact package for shipping. The construction of the skimmer will be such that the time and manpower necessary for breakdown and assembly is minimized (assembly on scene in two hours). As shown, the cross-beams must be removed from the skimmer as well as the fiber array and belt system,grating, guard rails, davit and tackle, and other miscellaneous items. The hulls will be strapped together and the fiber array and belt located on top of the hulls. Miscellaneous hardware and equipment such as the trash gate, grating, guard rails, davit and tackle, boom adaptor plates, and collapsible control stand enclosure (optional) would be

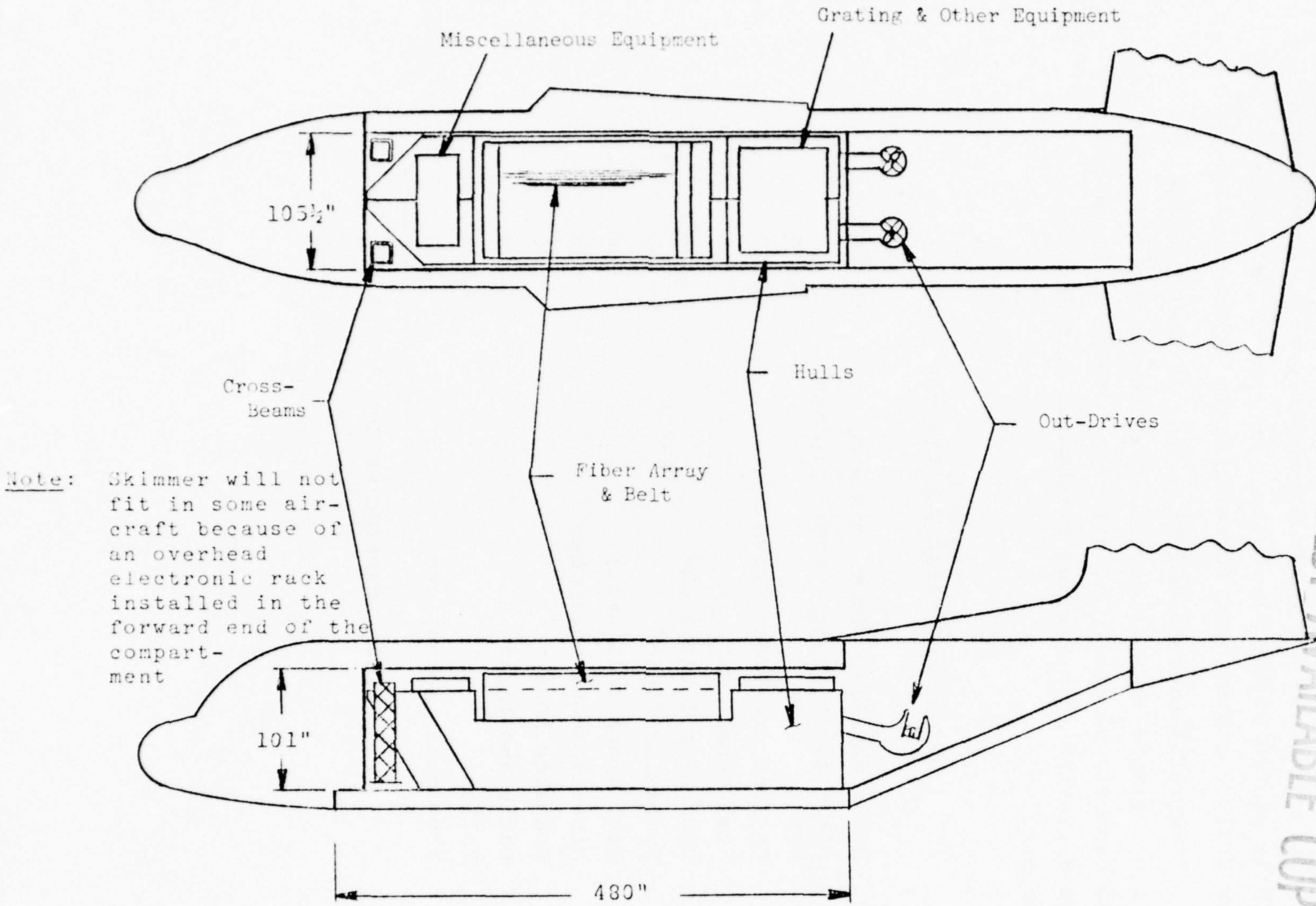


FIGURE 39
PROTOTYPE SKIMMER LOADED ON C-130 AIRCRAFT

stored atop the hulls, for and aft of the fiber array. Other items such as the control console, tools, and clothing would be stored within the hulls. As shown, the cross-beams will be stored just forward of the skimmer hulls.

The total overall weight of the skimmer package shall be no more than 25,000 pounds, the maximum allowable cargo capacity of the C-130 aircraft. Table 4, shown below, gives a listing of estimated weights as packaged for air transport.

TABLE 4
WEIGHT ESTIMATES FOR AIR TRANSPORT

Hulls and Misc. Eqpt.(maximum)	12,000 lbs.
Fiber array, belt system, piping, etc.	4,670
Engines and stern drive units	2,200
Fuel tanks	450
Hydraulic fluid tanks	300
Hydraulic fluid	450
Fuel (tank half full)	530
Miscellaneous equipment	480
Transfer hose	120
Davit and tackle	200
Pallet	3,400
Tie downs, tarps, etc.	200
TOTAL SHIPPING WEIGHT	25,000 lbs.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were reached during this phase of the development program:

1. The streaming fiber concept works -- a large-scale model proved effective in recovering oil at high speeds.
2. We have identified limitations in the system, principally in the areas of wave performance and viscous oil handling.
3. We have also identified design modifications which should remove these limitations and allow the system to meet or exceed all design goals.

The following recommendations are also made:

1. Develop the wave-conforming fiber array as the method for improving wave performance.
2. Develop the porous belt concept as a method of recovering oil that leaves the bottom of the fibers; such a method will improve performance in viscous oils, and in addition remove other limitations from the system.
3. Modify the existing large-scale model with the above developments, and retest at OHMSETT.
4. Proceed with prototype design and construction after OHMSETT tests.

6.0 REFERENCES

1. Beach, R. L., F. A. March, "Development of a Streaming Fiber Oil Spill Control Concept," Final Report to Coast Guard, Report No. G-D-35-75, Contract No. DOT-CG-40,217-A, March 1975.

2. Lindenmuth, W. T., T. R. Sundaram, A. M. Sinnarwalla, "Fast Current Oil Response System, Stage I, SVROS Development," Final Report to Coast Guard, Report No. G-D-36-75, Contract No. DOT-CG-40,218-A, March 1975.

3. P. Becher, Emulsions: Theory and Practice, 2nd Edition, Reinhold Publishing Corp., New York, 1965.

4. Wicks III, M., "Fluid Dynamics of Floating Oil Containment by Mechanical Barriers in the Presence of Water Currents," Proceedings of the Joint Conference on Prevention and Control of Oil Spills, American Petroleum Institute, Dec., 1969, pp. 55-106.

5. "Evaluation and Testing of Pumping and Handling Systems for Oil-Solids Mixtures," JBF Scientific Corporation, Report to Naval Civil Engineering Laboratory, Contract No. N62399-73-C-0030, June 1974.

6. Beach, R. L., F. A. March, L. S. Brown, T. S. McMahon, J. Papp, D. E. Laaksonen, "Development of a High Seas Oil Recovery System, Phase II," Final Report to Coast Guard, Contract No. DOT-CG-22651A, June 1973.

7. Moses, R. O., and Sandra Blackstone, "Fiber Belt Oil Recovery System," Final Report to Coast Guard, Report No. CG-D-82-74, Contract No. DOT-CG-14,058-A, December 1971.

APPENDIX

TEST REPORT

DAVIDSON LABORATORY, STEVENS INSTITUTE OF TECHNOLOGY

STEVENS INSTITUTE OF TECHNOLOGY

DAVIDSON LABORATORY
CASTLE POINT STATION
HOBOKEN, NEW JERSEY

Letter Report SIT-DL-76-1876

March 1976

FAST-CURRENT SKIMMER MODEL TESTS

by

E. Numata

for

Seaward International
Purchase Order 003565
DL Project 4372/658

A 1/5-scale model of a fast-current oil skimming catamaran was towed in calm water and in irregular head and following seas to measure resistance and motions. When skimming oil, the underwater space forward of amidships between the hulls is fitted with an array of longitudinal streaming fibers; water flow over the fibers was observed in smooth water and waves.

The tests were conducted during the period 23-27 February 1976. Messrs. R. J. Powers and R. L. Beach of Seaward International, and R. W. Ard and D. S. Jensen of the U. S. Coast Guard observed the testing.

MODEL

1/5-scale wood models of the catamaran hulls were constructed by Seaward International, together with a scale model of the fiber array, hereafter referred to as the "fiber box." Figure 1 shows the vessel configuration.

Davidson Laboratory installed a towing pivot assembly on the midship thwart spanning the two hulls, and installed removable ballast weights so that the following prototype test conditions were accurately represented on model scale.

Draft, ft	2	2	3
Trim angle, deg	0	1.35	0
Displacement vol, cu.ft	465	465	703
LCG forward of stern, ft	17.6	16.4	17.7
VCG above keel, ft	2.4	2.4	2.1
Pitch gyradius	12	12	12
Roll gyradius	5.2	5.2	5.2

In those conditions where the fiber box was installed, ballast was adjusted to maintain the same draft and trim as without the box.

FAST—CURRENT SKIMMER -- OPERATING

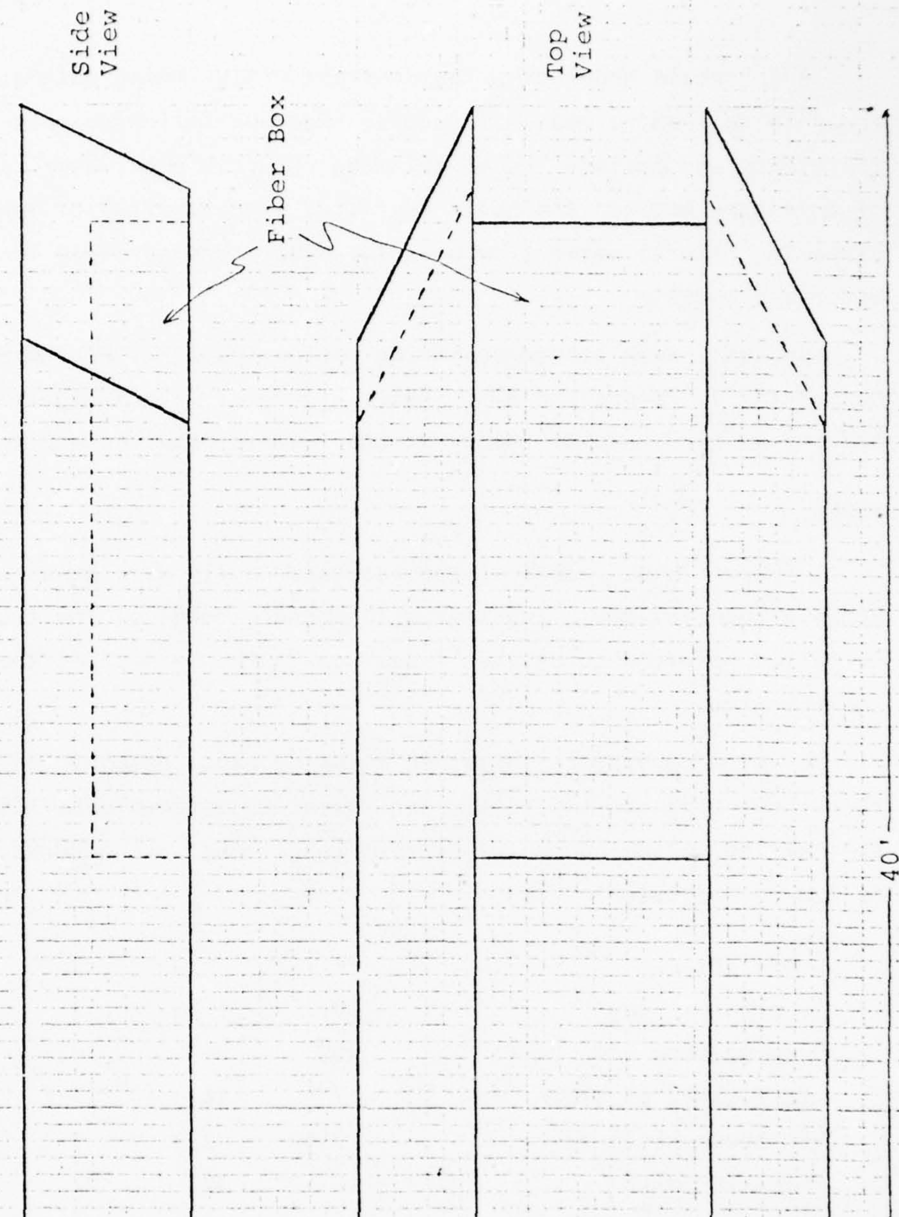


FIGURE 1

Free oscillation tests in still water were conducted and the following natural periods were measured; the number of well-defined cycles used in calculating the average period are noted in parentheses.

Draft, ft	2	3
Fiber Box	Out	In
Natural Periods, sec		
Pitch	2.2(2)	2.7(1)
Heave	2.0(2)	2.4(5)
Roll	-	2.5(5)

TEST PROCEDURES

All testing was conducted in DL Tank 3, 313 ft x 12 ft x 5.5 ft deep in fresh water with a temperature of 69°F.

In smooth water, drag, trim and heave at the CG were measured. Signals from the drag balance, trim clinometer and heave pulley were transmitted by overhead cables from the towing carriage to shoreside signal conditioning units. Conditioned signals were time-averaged on the tankside PDP-8e digital computer which produced teletype printouts of results in engineering units. A 2-$\frac{1}{4}$ x 2-$\frac{1}{4}$ black-and-white picture was taken during each run to document the flow pattern at the bow between the hulls.

In waves, drag, pitch and heave at the CG were measured. Conditioned signals were recorded on chart paper and on magnetic tape. After digitizing each time history on-line, the computer evaluated and averaged the peaks and troughs, printing out a mean value, and significant (average of 1/3 highest) and maximum values of oscillation peaks and troughs; the number of oscillations were also recorded. Data were recorded during constant speed runs of 140 ft in tank length when running in head and following seas. At higher speeds multiple runs were taken in different sections of the wave pattern to obtain an adequate number of encounters for statistical reliability.

Two runs were made at zero speed in beam seas to measure rolling motions. A gyro was mounted on the midship thwart of the model to sense rolling motion. The output of the signal conditioner was recorded on chart paper.

Prior to conducting the wave tests, two reproducible irregular sea states were calibrated. Figure 2 shows the measured spectra of these two seas, expanded to prototype scale; also shown for reference are the one-parameter Pierson-Moskowitz theoretical spectra having the same significant heights.

Time-scaled 16mm color motion pictures were taken of portions of selected test runs. When viewed at a projection speed of 16 frames per second, the prototype time scale is represented.

TEST RESULTS

All test data have been expanded to prototype scale and are presented in tabular form.

Tables 1 and 2 present smooth water results for resistance, EHP, trim and heave.

Tables 3, 4 and 5 present results of tests in waves.

Table 6 lists some observations made during both smooth water and wave tests.

Table 7 is the sequence of motion pictures; Table 8 identifies all runs.

CONCLUDING REMARKS

The simple hull configuration is appropriate for practical, inexpensive fabrication. However, the bow knuckle and the fully-immersed transom add significantly to the resistance when running without the fiber box.

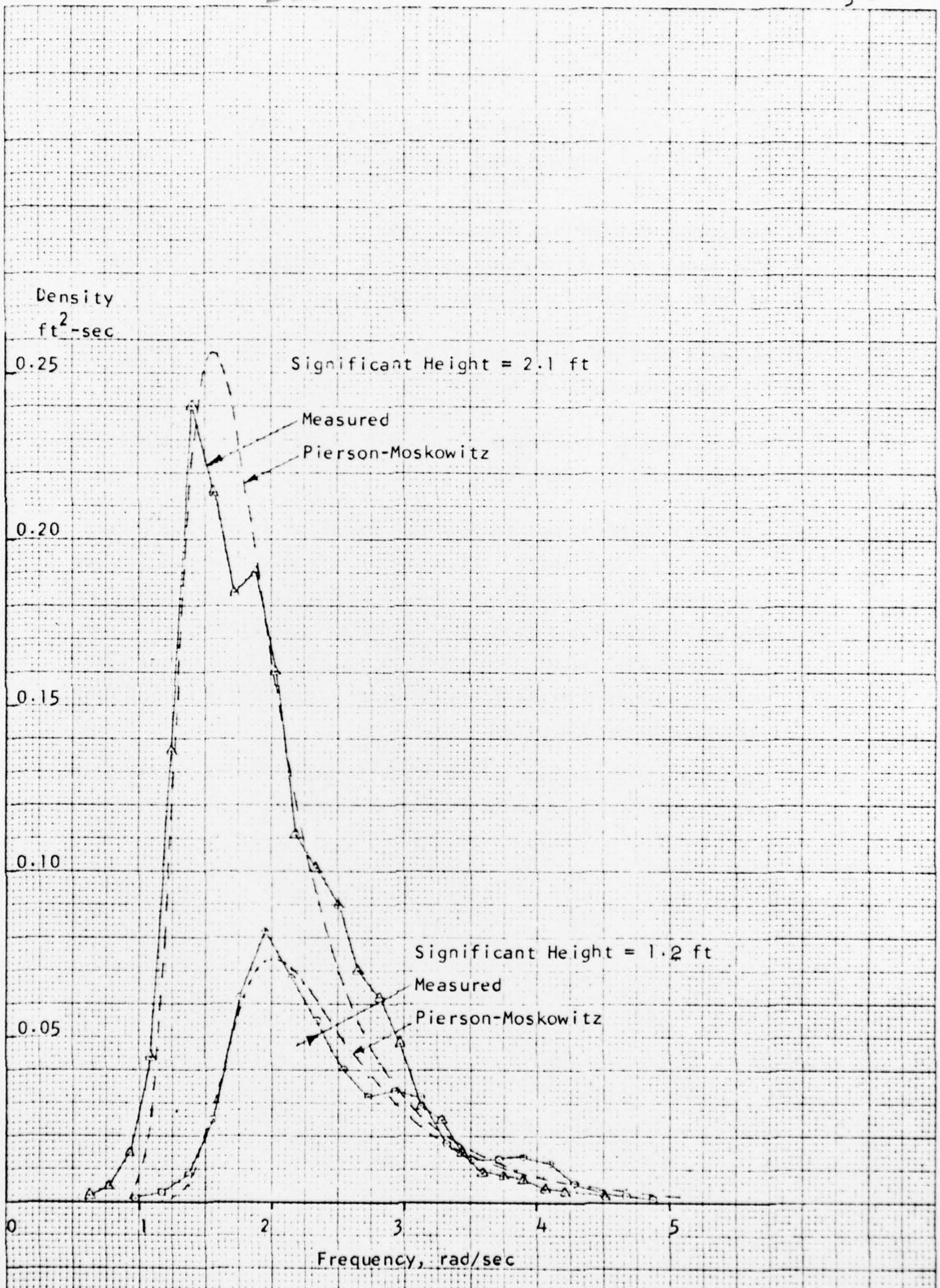


Figure 2 Wave Spectra

NOTES ON PREDICTIONS OF FULL-SCALE PERFORMANCE IN SMOOTH WATER

1. Resistance and EHP are for salt water at 59°F based on the 1947 ATTC model-ship correlation coefficients (Schoenherr) with an addition of .0004 for surface roughness of clean hull.

2. Heave is vertical displacement of CG from its at-rest location; (-) indicates downward heave.

3. Trim is angular displacement of vessel from its at-rest attitude; (-) indicates bow down trim.

4. The model towpoint was at deck level whereas propulsive thrust is to act at keel level. Accordingly, a bow-up moment equal to the product of towing force times distance from towpoint to keel was applied during a test run to simulate the effect of thrust applied at keel level. In those runs where such a moment was omitted, measured trims are shown and, alongside in parentheses, estimated corrected trims.

5. When the fiber box was raised 8-3/4 inches, the top fibers were approximately 1 inch below the water surface.

TABLE 1

FULL-SCALE PREDICTIONS

Smooth Water, 2 Ft Draft

Speed knots	Drag lb	EHP	Heave ft	Trim deg
1. Bare Hull, Zero Static Trim				
3.0	160	1.5	0	-.10
6.0	920	17.0	-.1	-.55(-.35)
8.0	2290	56.3	-.3	-1.25(-.75)
9.0	2850	79.0	-.4	-1.00(-.40)
10.0	3550	109.2	-.5	.10(.85)
2. Bare Hull, 1.35° Bow Up Static Trim				
3.0	180	1.6	0	-.10
6.0	920	17.0	-.1	-.45(-.25)
8.0	2160	53.2	-.2	-.90(-.45)
9.0	2620	72.5	-.3	-.45(.10)
10.0	3260	100.2	-.3	.60(1.30)
11.0	3900	131.7	-.1	3.15
12.0	4210	155.0	-.1	2.30(3.20)
13.0	4270	170.8	.3	4.55
3. With Fiber Box (Lowest Position), Zero Static Trim				
3.0	590	5.5	-.4	-.35
5.0	2180	33.4	-.2	-.25

TABLE 2

FULL-SCALE PREDICTIONS

Smooth Water, 3 Ft Draft, Zero Trim

Speed knots	Drag lb	EHP	Heave ft	Trim deg
1. Bare Hull				
3.0	250	2.4	0	-.10
6.0	1280	23.5	-.15	-.50(-.20)
7.0	2350	50.4	-.25	-.65(-.15)
8.0	3370	82.8	-.40	-1.75(-1.05)
2. With Fiber Box at Lowest Position				
2.0	450	2.8	-.05	-.05
4.0	2110	26.0	-.25	-.20(.25)
5.0	3790	58.1	-.40	-.35(.45)
5.5	4880	82.5	-.50	-.45(.60)
3. With Fiber Box Raised 8-3/4 Inches				
4.0	1670	20.5	-.20	0
5.5	3600	60.9	-.40	.35

NOTES ON PRESENTATION OF
FULL-SCALE RESULTS IN SEA STATES

1. Drag predictions are for salt water at 59°F based on the 1947 ATTC model-ship correlation coefficients (Schoenherr) with an addition of .0004 for surface roughness of clean hull.

2. The number of wave encounter cycles is assumed equal to the number of pitch oscillation cycles recorded.

3. Mean pitch angle is referred to the at-rest attitude in still water; (-) mean pitch is bow down. Significant and maximum amplitudes are also referred to the at-rest datum.

4. Mean heave is vertical displacement of vessel CG from its at-rest location in still water; (-) mean heave is downward. Significant and maximum amplitudes are also referred to the at-rest datum.

5. When the fiber box was raised 8-3/4 inches, the top fibers were approximately 1 inch below the surface.

TABLE 3

HEAD SEAS, 2 FT DRAFT

Speed knots	Signif. Ht ft	Encount. Cycles	Drag lb	Pitch, deg. Mean	Pitch Significant Up	Pitch Significant Down	Pitch Maximum Up	Pitch Maximum Down	Heave, ft. Mean	Heave Significant Up	Heave Significant Down	Heave Maximum Up	Heave Maximum Down
Bare Hull, 1.35° Static Bow Up Trim													
0	2.1	106	20	-0.1	2.2	2.3	3.4	3.3	0	0.6	0.6	0.9	0.8
3.0		106	360	0	2.3	2.2	3.3	3.1	0	0.6	0.6	0.9	0.9
5.0		106	860	0.1	2.0	1.9	2.7	2.7	-0.1	0.6	0.8	0.8	1.0
7.0		80	1860	0.2	1.8	1.4	3.1	1.9	-0.2	0.5	0.8	0.8	1.0
9.0		80	2760	0.1	1.6	1.3	2.1	1.8	-0.3	0.3	1.0	0.5	1.1
9.0*		19	2720	-0.1	1.1	1.4	1.4	1.7	-0.3	0.3	0.9	0.4	1.0
10.0*		19	3440	-1.0	0.3	2.3	0.9	3.0	-0.2	0.4	1.0	0.4	1.2
With Fiber Box in Lowest Position, Zero Static Trim													
2.0	1.2	77	330	0.1	1.1	1.0	1.8	1.6	0	0.2	0.3	0.3	0.4
3.5		48	1080	0.2	1.0	0.7	1.5	1.2	-0.1	0.1	0.4	0.2	0.5
5.0*		36	2480	0	0.8	0.7	1.0	0.9	-0.3	0.1	0.5	0	0.6
2.0	2.1	70	500	0.1	2.1	1.9	2.9	2.8	-0.1	0.5	0.7	0.7	0.9
3.5		42	1280	0.2	2.2	1.7	3.1	2.4	-0.2	0.4	0.8	0.7	1.1
5.0*		35	2730	0.1	1.6	1.3	2.1	2.0	-0.3	0.3	0.9	0.4	1.0

*Bow-up moment applied to simulate thrust at keel level.

TABLE 4

HEAD SEAS, 3 FT DRAFT

Speed knots	Signif. Ht ft	Encount.	Drag	Pitch, deg. Mean	Pitch Significant Up	Pitch Significant Down	Pitch Maximum Up	Pitch Maximum Down	Heave, ft. Mean	Heave Significant Up	Heave Significant Down	Heave Maximum Up	Heave Maximum Down
Fiber Box in Lowest Position													
2.0	1.2	74	550	0	1.1	1.0	1.7	1.5	-0.1	0.1	0.3	0.3	0.4
3.5	|	45	1730	0.1	0.9	0.7	1.4	1.2	-0.2	0	0.5	0.1	0.6
Fiber Box Raised 8-3/4 inch													
0	1.2	100	0	0	1.3	1.3	2.2	2.1	0	0.2	0.3	0.3	0.4
2.0	|	85	460	0.1	1.2	1.1	1.9	1.7	-0.1	0.2	0.4	0.5	0.7
3.5	|	94	1340	0.1	0.9	0.7	1.4	1.2	-0.2	0	0.4	0.1	0.5
5.0*	|	106	3100	-0.2	0.6	0.9	1.0	1.3	-0.4	-0.2	0.6	-0.1	0.9
0	2.1	100	50	-0.1	2.2	2.3	3.3	3.1	-0.1	0.5	0.7	0.9	0.9
2.0	|	69	600	0	2.3	2.2	2.7	2.8	-0.1	0.5	0.7	0.8	1.0
3.5	|	82	1630	0.1	2.3	1.9	3.2	2.8	-0.2	0.5	0.8	0.6	1.1

*Bow-up moment applied to simulate thrust at keel level.

TABLE 5
FOLLOWING AND BEAM SEAS
3 FT DRAFT
WITH FIBER BOX

Following Seas, 2.1 ft Significant Height

Speed, knots	3.6		5.1	
Encounter cycles	21		18	
Drag, lb	1440		3050	
Pitch, deg.	Up	Down	Up	Down
Mean	0.1		0.1	
Significant	1.6	1.4	1.0	0.7
Maximum	2.3	1.7	1.2	1.0
Heave, ft				
Mean		0.1		0.3
Significant	0.4	0.7	0	0.7
Maximum	0.6	0.8	0	0.8

Beam Seas, Zero Speed

Significant height, ft		1.2		2.1
Encounter cycles		100		100
Roll, deg, seaward hull	Up	Down	Up	Down
Significant	5.8	6.2	8.8	7.9
Maximum	8.0	7.8	12.5	11.8

TABLE 6
VISUAL OBSERVATIONS

Smooth Water

a. 2 Ft Draft

Bow wave does not reach foredeck. Flow does not break clear of transom below 10 knots.

b. 3 Ft Draft

With fiber box in lowest position, bulkhead at aft end of fiber box causes a rise in water level at the bulkhead which reaches just below deck level at 5.5 knots. When fiber box is raised, water rise at bulkhead is less.

Waves

a. 2 Ft Draft, 1.35° Trim, 2.1 Ft Head Seas

At speed of 3 and 5 knots there is moderate pounding at the bow; at 7 knots and above there is no pounding. At 3 and 5 knots pounding averaged once every 15 encounters.

Water was shipped on the foredeck in small to moderate amounts as follows; at zero speed there were no occurrences.

Speed, knots	3	5	7	9
Avg. encounters between occurrences	35	20	10	80

b. 3 Ft Draft with Fiber Box

In both 1.2 ft and 2.1 ft head seas there was no discernible bow pounding, but there were numerous wave impacts against the box end bulkhead which increased in intensity with speed and wave height.

Water was shipped on the foredeck in small to moderate amounts as follows:

Table 6 (continued)

Speed, knots	0	2	3.5	5
Avg. encounters between occurrences				
1.2 ft waves	50	*	25	8
2.1 ft waves	25	9	6	**

In 2.1 ft following seas there were no discernible cases of pounding, impacts, or water on deck.

In beam seas at zero speed there was a small amount of water shipped about once every 35 encounters in 1.2 ft seas, and a moderate amount every 15 encounters in 2.1 ft seas.

* no occurrences

** not tested

TABLE 7

MOTION PICTURE SEQUENCE

16 mm, color, silent; 20 minutes viewing time

Run	Draft ft	Fiber Box Immerson	Signif. Ht. ft	Speed knots
33	2	Out	2.1	5.0
36	2	Out	2.1	7.0
39	2	Out	2.1	9.0
43	3	Lowest	1.2	2.0
45	3	Raised	1.2	2.0
47	3	Raised	1.2	3.5
50	3	Raised	1.2	5.0
53	3	Raised	2.1	2.0
55	3	Raised	2.1	3.5
63	2	Lowest	1.2	5.0
65	2	Lowest	2.1	3.5
66	2	Lowest	2.1	5.0
71	2	Out	2.1	10.0
75	3	Raised	1.2	0
76	3	Raised	2.1	0

TABLE 8

TEST RUNS IN SMOOTH WATER

Run No.	Draft ft	Fiber Box Immersion	Static Trim deg	Speed kt	Picture No.
2	3	Lowest	zero	2.0	1-1
3				4.0	2
4				5.0	3
5				5.5	4
6		Out		3.0	5
7				6.0	6
8				7.0	7
9				Aborted	8
10				8.0	9
11	2			3.0	10
12				6.0	11
13				8.0	12
14				9.0	2-1
15				10.0	2
16			1.35	3.0	3
17				6.0	4
18				8.0	5
19				9.0	6
20				10.0	7
21				12.0	8
22				12.0	9
57	3	Raised	zero	5.5	
58	3	Raised		4.0	
59	2	Lowest		3.0	
60		Lowest		5.0	
67		Out	1.35	11.0	3-2
68				13.0	
69				13.0	3

TABLE 8 (cont'd)

TEST RUNS IN WAVES

Run No.	Draft ft	Heading	Fiber Box Immersion	Static Trim deg	Signif Height ft	Speed kt
30	2	Head	Out	1.35	2.1	3.0
31						
32						5.0
33						
34						
35						7.0
36						
37						
38						9.0
39						
40						
41						
42						0
43	3		Lowest	zero	1.2	2.0
44						3.5
45			Raised			2.0
46						3.5
47						
48						5.0
49						
50						
51						
52						0
53					2.1	2.0
54						3.5
55						
56						0
61	2		Lowest		1.2	2.0
62						2.5
63						5.0
64*					2.1	2.0
65						3.5
66						5.0
70			Out	1.35		9.0
71						10.0
72	3	Stern	Raised	zero		5.0
73						3.6
75		Beam			1.2	0
76					2.1	0

*Picture No. 3-1